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S.C. Zoz & M.B. Pate

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Iowa State University
2088 H.M. Black Engineering Building
Ames, Iowa 50011-2160

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The report gives results of miscibility, solubility, and viscosity measurements of refrigerant R-236ea with three potential lubricants. The lubricants were a mineral oil, alkylbenzene, and polyol ester, each with a nominal viscosity of 68 cSt. The miscibility tests were performed in a test facility consisting of a series of miniature test cells in a constant-temperature bath. The bath temperature was precisely controlled over a range of -50 to 90 ^{0}C. The test cells are constructed to allow for complete visibility of the refrigerant/lubricant mixtures under all test conditions. Critical solution temperatures obtained from the miscibility data, both solubility and viscosity data were obtained for R-236ea and the most promising lubricant. These data were obtained for a refrigerant concentration range of 0 to 40 wt % refrigerant over a temperature range of 40 to 120 ^{0}C. This range of conditions represents the area of interest necessary for the proper design of compressors. For comparison purposes, data were also taken for the existing US Navy shipboard chiller refrigerant and lubricant concentration, namely R-114 and a naphthenic oil.

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MISCIBILITY, SOLUBILITY, AND VISCOSITY MEASUREMENTS FOR R-236EA WITH POTENTIAL LUBRICANTS

Prepared for

National Risk Management Research Laboratory

Prepared by

National Risk Management
Research Laboratory
Research Triangle Park, NC 27711

FOREWORD

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MISCIBILITY, SOLUBILITY, AND VISCOSITY MEASUREMENTS FOR R-236EA WITH POTENTIAL LUBRICANTS

by

S.C. Zoz
M.B. Pate
Iowa State University
Ames, IA 50011

EPA Cooperative Agreement No. CR 820755-01-4

Project Officer:

Theodore G. Brna
U.S. Environmental Protection Agency
National Risk Management Research Laboratory
Air Pollution Prevention and Control Division
Research Triangle Park, NC 27711

Prepared for:

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ABSTRACT

Miscibility, solubility, and viscosity data are needed to determine the suitability of refrigerant/lubricant combinations for use in refrigeration systems. Miscibility data have been obtained for R-236ea and three potential lubricants. The lubricants consist of a mineral oil, alkylbenzene, and polyol ester, each with a nominal viscosity of 68 cSt. The miscibility tests were performed in a test facility consisting of a series of miniature test cells submerged in a constant temperature bath. The bath temperature can be precisely controlled over a temperature range of -50°C to 90°C (-58°F to 194°F). The test cells are constructed to allow for complete visibility of refrigerant/lubricant mixtures under all test conditions. Critical solution temperatures obtained from the miscibility data are presented for each refrigerant/lubricant combination.

In addition to miscibility data, both solubility and viscosity data were obtained for R-236ea and the most promising lubricant. These data were obtained for a refrigerant concentration range of 0 to 40 weight percentage refrigerant over a temperature range of 40°C to 120°C. This range of conditions represents the area of interest necessary for the proper design of compressors. For comparison purposes, data were also taken for the existing refrigerant and lubricant concentration, namely R-114 and a naphthenic oil.

This report was submitted in fulfillment of CR 820755-01-4 by Iowa State University under the sponsorship of the U.S. Environmental Protection Agency with funding from the Strategic Environmental Research and Development Program.* This report covers a period from October 1992 to March 1995.

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CHAPTER 1

INTRODUCTION

MISCIBILITY OF R-236ea AND LUBRICANT MIXTURES

The development of acceptable alternative refrigerants requires the identification of compatible lubricants so that refrigeration systems with mechanical compressors will operate properly. The first requirement of a compatible lubricant is that it be miscible with the refrigerant over the operating temperatures of the system. Refrigeration systems require a miscible refrigerant/lubricant mixture for compressor lubrication, for maximum heat transfer performance in the evaporator, and for proper lubricant return to the compressor. Therefore, miscibility data were taken in this study.

To obtain miscibility data, one must visually observe and record the physical conditions of a refrigerant/lubricant mixture at specific temperatures. The procedure is repeated for desired ranges of temperatures and refrigerant concentrations. Visual inspection of the mixture allows for determination of whether the mixture showed signs of cloudiness, floc or precipitate formation, and the formation of a second liquid phase.

The data obtained for this report were for HFC-236ea, hereafter designated as R-236ea, with an ISO68 pentaerythritol ester mixed-acid lubricant, and for CFC-114, hereafter designated as R-114, with an ISO68 naphthenic mineral oil.

Initial miscibility tests were performed on R-236ea/lubricant mixtures for refrigerant concentrations of 25 and 50% by weight. Additional tests were performed for refrigerant concentrations of 75 and 95% when the initial tests showed complete miscibility (that is, miscible over the entire test temperature range). These tests were performed by keeping the refrigerant/lubricant mixture visible at all times, by controlling temperatures to ±1°C (±1.8°F), and by moving the test cells to mix the contents. Each refrigerant/lubricant combination was tested for miscibility in 10°C (18°F) increments over the test temperature range of -40 to +90°C (-40 to +194°F).

SOLUBILITY, DENSITY, AND VISCOSITY OF REFRIGERANT/LUBRICANT MIXTURES

To ensure refrigerant/lubricant compatibility, designers require accurate and extensive data on the solubility, density, and viscosity of alternative refrigerant and lubricant mixtures. To aid potential users of HFC-236EA, data on the viscosity, density, and solubility of lubricant/refrigerant mixtures at various pressures and temperatures were taken in this study. Specifically, tests were conducted on R-236ea/ISO68 pentaerythritol ester mixed-acid mixtures and R-114/ISO68 naphthenic mineral oil mixtures.

Existing data on the viscosity and solubility of lubricant/refrigerant pairs are limited. Before 1990, data were available only at temperatures less than 60°C (140° F). Recently, in an ASHRAE-sponsored research project, RP-580, Van Gaalen et al. (1991a, 1991b) developed methods of obtaining these data at temperatures up to 150°C (302°F) and for pressures up to 3.5 MPa (500 psia). This research was completed at Iowa State University for R-22 and R-502 with several different lubricants [Van Gaalen et al. (1990 and 1991a, 1991b)]. Since then, further data have been gathered with the property test facility, including the data presented here.

The objective of this research was to obtain data which will be useful for the design of refrigerant compressors. Specifically, the data obtained include the solubility, viscosity, and density of lubricant/refrigerant mixtures subjected to the following conditions.

Composition:	0 to 40 weight percent refrigerant
Temperature:	40°C to 120°C (104°F to 248°F)
Pressure:	0 to 3.5 MPa (0 to 500 psia)

The following sections discuss the test facility and the methodology which have been developed to obtain the required data. The data are also tabulated, and uncertainties are documented. Additionally, results for the lubricant/refrigerant pairs studied are presented in the form of graphs, tables, and empirical correlations.

CHAPTER 2

CONCLUSIONS

MISCIBILITY OF R-236ea AND LUBRICANT MIXTURES

Critically needed miscibility data have been obtained for R-236ea and three lubricants. The test facility incorporates test cells with sight windows that, when valves are screwed into opposing ports, serve as pressure vessels. The cells were charged with variable amounts of refrigerant and lubricant to facilitate refrigerant compositions from 0 to 100%. Operating temperatures and pressure ranges for the facility are -50°C to 90°C (-58°F to 194°F), and 0 to 3.5 MPa (0 to 500 psia), respectively.

Data for the R-236ea in each of the test lubricants have been collected for refrigerant concentrations of 25 and 50%. The raw data were presented and the results were summarized. The pentaerythritol ester mixed-acid (ISO68) lubricant was found to be completely miscible over the temperature and concentration ranges tested; while the naphthenic mineral oil and alkylbenzene lubricant were found to be immiscible over most of the temperature range tested. Additional data for the pentaerythritol ester mixed-acid (ISO68) lubricant were taken at 75% and 95% refrigerant.

SOLUBILITY, DENSITY, AND VISCOSITY OF REFRIGERANT/LUBRICANT MIXTURES

A lubricant/refrigerant test facility has been described, a methodology has been developed to provide critically needed property data, and data have been obtained and correlated at high pressures and temperatures for several lubricant/refrigerant mixtures. The test facility can be used for determination of the solubility, viscosity, density, and miscibility of lubricant/refrigerant mixtures. The facility incorporates a commercially available viscometer, as well as windows for observation of the contents. The viscosity measurement range is from 1 cp to 200 cp, but this range may be easily extended. Precise and convenient charging of mixtures with refrigerant compositions ranging from 0 to 100% can be provided. Operating temperature and pressure ranges for the test facility are 20°C (68°F) to 150°C (302°F) and 0 to 3.5 MPa (0 to 500 psia), respectively.

Experimental procedures for the operation of the test facility have been described. Data reduction techniques, including the correlating equations, were outlined. The facility has been successfully employed to obtain experimental results for R-236ea/ISO68 pentaerythritol ester mixed-acid and R-114/ISO68 naphthenic mineral oil mixtures. These tests provide solubility, density, and viscosity information for temperatures as high as 100°C (212°F) and for refrigerant mass fractions from 0 to 50%, subject to a maximum pressure limitation of 1.4 MPa (200 psia). The results are presented as solubility, viscosity, and density charts and graphs that give pressure, liquid viscosity, and liquid density as functions of temperature and refrigerant concentration. Empirical correlating equations (applicable only over the range of data collected) that allow convenient interpolation of the data are also presented.

CHAPTER 3

RECOMMENDATIONS

The following recommendations are made based upon the results of this study.

1. When R-236ea is used as a replacement refrigerant for R-114, an ISO68 pentaerythritol ester mixed acid can be used as a replacement lubricant based on miscibility, solubility, and viscosity considerations.

2. If other refrigerants are considered as potential replacements for R-114, then the scope of this study should be repeated for the new refrigerant.

3. Many commercially available lubricants contain additives which are optimized based on wear and corrosion considerations for a particular refrigerant and application. A study of additives should be undertaken by any lubricant manufacturer before the lubricant is marketed.

CHAPTER 4

MISCIBILITY OF R-236ea AND LUBRICANT MIXTURES

REFRIGERANT/LUBRICANT TEST FACILITY

The test facility for measuring miscibility includes test cells capable of withstanding the high pressures and the extreme temperatures encountered in the study of refrigerant/lubricant mixtures. The facility was designed for the purpose of determining the miscibility characteristics of refrigerant/lubricant mixtures over the temperature range of -50°C to 90°C (-58°F to 194°F) and for pressures up to 3.5 MPa (500 psia). The test cells have glass viewports and are submerged in one of two constant temperature baths so that the miscibility characteristics of the mixture can be observed and recorded. The test facility is described in detail in a previous publication (Zoz, 1994 and Zoz and Pate, 1993).

The precise temperature of each bath fluid was measured by a platinum resistance temperature detector (RTD) that is connected to a signal conditioner/current transmitter. The RTDs have an accuracy of ±0.1°C (±0.18°F). Since the miscibility characteristics of mixtures in each cell were noted at 10°C (18°F) intervals in this study, the uncertainty in the actual temperature where a change in the miscibility characteristics occurred is ±5°C (±9°F). Due to the magnitude of this latter uncertainty, the uncertainty in the temperature measurements is insignificant.

Miscibility Characteristics

When a refrigerant/lubricant mixture is miscible, it appears as a homogeneous transparent solution. However, when a refrigerant/lubricant mixture is immiscible, there is either cloudiness, evidence of particles dispersed throughout the mixture, or there are two liquid phases present in the cell. Throughout all testing, visual inspections were made for these signs of immiscibility. The presence of two liquid phases was the only form of immiscibility observed in this study.

Refrigerant Concentration

The refrigerant concentration of each test cell was calculated from the total masses of refrigerant and lubricant charged into the cell. The uncertainty in the concentration measurements depends upon the concentration that is being considered, but the maximum uncertainty in concentration is ±0.001 (0.1%). The uncertainty was calculated by using a propagation-of-error method discussed by Beckwith et al. (1982).

It is important to note that the concentration in the test cell changed as the temperature of the cell was varied. This occurred because a vapor space was required above the liquid mixture so that the thermal expansion of the liquid mixture did not cause cell failure due to extremely high pressures internal to the cell. Due to the large uncertainty in the temperature at which a change in the miscibility characteristics occurred (i.e., ±5°C), small changes in the refrigerant concentration with temperature can be disregarded.

Critical Solution Temperatures

The critical solution temperature, as defined in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Refrigeration Handbook (1990), is the temperature above which a refrigerant/lubricant combination is miscible for all refrigerant concentrations. Since some of the new refrigerant/lubricant combinations have regions of immiscibility that occur with increasing temperature, an additional definition must be used. The lower critical solution temperatures presented herein are based on the ASHRAE definition, while the upper critical solution temperature is defined as the temperature below which a refrigerant/lubricant combination is miscible for all refrigerant concentrations. No regions of immiscibility occurring with increasing temperature were encountered in this study.

Some refrigerant/lubricant combinations were found to be immiscible over the entire test temperature range for certain concentrations. Other refrigerant/lubricant combinations never became immiscible (i.e., they were always miscible) regardless of the test temperature and concentration. For these cases, a critical solution temperature is not defined. Therefore, when presenting critical solution temperatures, these cases will be identified as immiscible (I) and miscible (M), respectively.

REFRIGERANT AND LUBRICANT SOLUTION RESULTS

This section presents results of miscibility measurements for each of three lubricants with R-236ea. The raw data are presented and also summarized. Each lubricant is commercially available and its trade name is also provided. Additionally, properties of the three lubricants are provided herein.

Lubricant Characteristics

Each lubricant is designated by its chemical type (base fluid) and viscosity. The viscosity presented is a nominal value as designated by the American Society for Testing and Materials (ASTM) standard D2422-86

(ASTM 1988). Table 4.1 provides densities and viscosities at various temperatures along with the flash points and pour points for each of the lubricants. Table 1 also provides the trade name of each lubricant.

TABLE 4.1: TEST LUBRICANT PROPERTIES

Lubricant (Viscosity) trade name	Viscosity cSt	Density g/mL	Pour Point (°C)	Flash Point (°C)
naphthenic mineral oil (ISO68) Suniso 4GS	62.5@38°C 6.0@99°C	0.916@ 20.0°C	-34.4	179
alkylbenzene (ISO68) Zerol 300	57.0@40°C 5.8@100°C	0.871@ 15.6°C	-40.0	155
pentaerythritol ester mixed-acid (ISO68) Castrol SW68	68.0@40°C 8.8@100°C	0.980@ 20.0°C	-39.0	250

Test Results

Results of the measurements of R-236ea in each lubricant are presented below. For every refrigerant/ lubricant combination investigated, the data set consists of the concentration, temperature, and visual characteristics of the contents of the cell. Table 4.2 provides the test (raw) data for each lubricant and R-236ea/lubricant pair. Tables 4.3, 4.4, and 4.5 provide summaries of the data for each lubricant and R-236ea/lubricant pair. The pentaerythritol ester mixed-acid (ISO68) lubricant was found to be completely miscible over the temperature and concentration ranges tested; while the naphthenic mineral oil and alkylbenzene lubricant were found to be immiscible over most of the temperature range tested. Additional data were taken at 75% and 95% refrigerant for the pentaerythritol ester mixed-acid (ISO68) lubricant since the 25% and 50% mixtures showed complete miscibility.

TABLE 4.2: MISCIBILITY RAW DATA

mass fraction of lubricant	naphthenic mineral oil (ISO68)		alkylbenzene (ISO68)		pentaerythritol ester mixed-acid (ISO68)			
temp. (°C)	0.249	0.477	0.216	0.484	0.213	0.436	0.772	0.946
89.7	2 phase	2 phase	clear	2 phase	clear	clear	clear	clear
78.8	2 phase	2 phase	clear	2 phase	clear	clear	clear	clear
69.6	2 phase	2 phase	clear	2 phase	clear	clear	clear	clear
60.3	2 phase	2 phase	clear	2 phase	clear	clear	clear	clear
49.4	2 phase	2 phase	2 phase	2 phase	clear	clear	clear	clear
40.1	2 phase	2 phase	2 phase	2 phase	clear	clear	clear	clear
23.2	2 phase	2 phase	2 phase	2 phase	clear	clear	clear	clear
14.1	2 phase	2 phase	2 phase	clear	clear	clear	clear	clear
-3.4	2 phase	2 phase	2 phase	2 phase	clear	clear	clear	clear
-9.6	2 phase	2 phase	2 phase	2 phase	clear	clear	clear	clear
-21.6	2 phase	2 phase	2 phase	2 phase	clear	clear	clear	clear
-31.3	2 phase	2 phase	2 phase	2 phase	clear	clear	clear	clear
-40.2	2 phase	2 phase	2 phase	2 phase	clear	clear	clear	clear

Notes: (1) Mass fraction is the mass of lubricant divided by total mass.
(2) Clear refers to presence of single phase.

TABLE 4.3: SUMMARY OF MISCIBILITY DATA FOR R-236ea AND THE NAPHTHENIC MINERAL OIL (ISO68)

Refrigerant Mass Fraction	Observations
0.25	immiscible from -40 to 90°C
0.48	immiscible from -40 to 90°C

TABLE 4.4: SUMMARY OF MISCIBILITY DATA FOR R-236ea AND THE ALKYLBENZENE LUBRICANT (ISO68)

Refrigerant Mass Fraction	Observations
0.22	miscible from 50 to 90°C immiscible from -40 to 50°C
0.48	immiscible from -40 to 90°C

TABLE 4.5: SUMMARY OF MISCIBILITY DATA FOR R-236ea AND THE PENTAERYTHRITOL ESTER MIXED-ACID LUBRICANT (ISO68)

Refrigerant Mass Fraction	Observations
0.21	miscible throughout temperature range -40 to 90°C
0.44	miscible throughout temperature range -40 to 90°C
0.77	miscible throughout temperature range -40 to 90°C
0.95	miscible throughout temperature range -40 to 90°C

CHAPTER 5

SOLUBILITY, DENSITY, AND VISCOSITY OF REFRIGERANT/LUBRICANT MIXTURES

LUBRICANT/REFRIGERANT TEST FACILITY

The experimental equipment described in this section includes a multipurpose test cell capable of controlling the high temperatures and pressures encountered in the study of lubricant/refrigerant mixtures. The facility, which was developed as part of an ASHRAE-sponsored research project, is designed to measure solubility, viscosity, and density for any lubricant/refrigerant mixture over the temperature range of 20°C (68°F) to 150°C (302°F) and for pressures up to 3.5 MPa (500 psia). Additional features of the facility include an external flow loop for sampling and for the measurement of the liquid viscosity. Also, transducers for measuring the temperature and pressure are installed on the test cell.

Description of the Lubricant/Refrigerant Test Facility

The major components of the facility are housed in an enclosure as shown in Figure 5.1. These components include the test cell, the viscometer and sampling loops, and a temperature control flow loop. These system components, as well as instrumentation for data acquisition and methods of injecting fluids into the test cell, are described in the following sections.

Test Cell

The test cell is a cylinder constructed of Schedule 120 Type 304 stainless steel pipe. It has an outside diameter of 141.3 mm (5.563 in.) and a wall thickness of 12.7 mm (0.500 in.). The test cell stands upright on one end so that the height of the internal volume is 457.2 mm (18 in.). Two diametrically opposite slots 317.5 mm (12.5 in.) in length are machined through the cylinder wall so that windows can be bolted into position. The windows allow for visual inspection of the contents at all times and under all test conditions. Figure 2.2 shows a schematic drawing of the test cell.

Flanges are welded to the pipe section at each end so that 25.4 mm (1 in.) thick end plates can be bolted on. The pressure (and vacuum) seal is provided by o-rings seated in machined grooves in the wall of the pipe section.

Three temperature probes and a heating/cooling coil enter the test cell through the top end plate, as depicted in Figure 5.2. Ports for pressure measurement, pressure relief, and for filling and evacuation of the test cell are also provided in the top plate. Two ports are machined into the bottom plate. As shown in Figure 5.2, these ports allow for the exit and return of fluid to/from the external viscometer and sampling loops.

The volume of the test cell and associated loops were determined and the scales on the windows calibrated by injecting precise amounts of R-113 at 20°C. The overall volume was measured as 5190 mL $\pm$ 20 mL (316.5 in.^{3} $\pm$ 1.2 in.^{3}). Calibration of the scales is accomplished by noting the height of the liquid level after each of several incremental injections of R-113. Thus, the liquid volume can be correlated with liquid level height. Therefore, with the total volume known, the vapor volume at each liquid level height is also known. Since the room temperature vapor density of R-113 is small, the amount of R-113 present in the vapor during this calibration procedure is negligible.

A heating/cooling coil enters and exits through the top of the cell. This coil is in direct thermal contact with the fluid in the cell. Two other coils are soldered onto the exterior of the test cell. The temperature, and hence pressure, of the solution under test is then controlled by pumping a constant temperature fluid through these coils. The heating fluid is supplied to the coils by a circulating bath. The presence of the three coils helps minimize the thermal gradients in the lubricant/refrigerant mixture. Additionally, to minimize the heat loss to the environment, a 51-mm (2-in.) thick layer of insulation is wrapped around the test cell.

Windows

Two diametrically opposite vertical windows are provided on the test cell wall. These windows allow for the viewing of the contents of the test cell for density determinations, for detecting the presence of more than one liquid phase, and for aiding the charging of the test cell. The viewing slots can be seen in Figure 5.1. The slots are 304.8 mm (12.0 in.) long and 12.7 mm (0.50 in.) wide. Scales are fastened to the test cell adjacent to the viewing slots. Therefore, the height of the liquid-vapor interface can be measured to within $\pm$0.76 mm (0.03 in.), which corresponds to an uncertainty in the volumes of liquid and vapor present to within $\pm$9 mL. This is less than 0.2% of the total cell volume. Each window contains two o-rings that provide the pressure seal. These o-rings must be compatible with the lubricant/refrigerant mixtures which will be tested. Viton o-rings were used with all refrigerant/lubricant mixtures tested in this study.

Temperature Control Flow Loop

A schematic diagram of the flow loop for controlling the temperature of the test cell is shown in Figure 5.2. The loop has three coils of 9.53 mm (0.375 in.) OD Type 304 stainless steel tubing. One is immersed in the test cell through the top plate, and the other two are soldered in place on the outside walls of the test cell. The

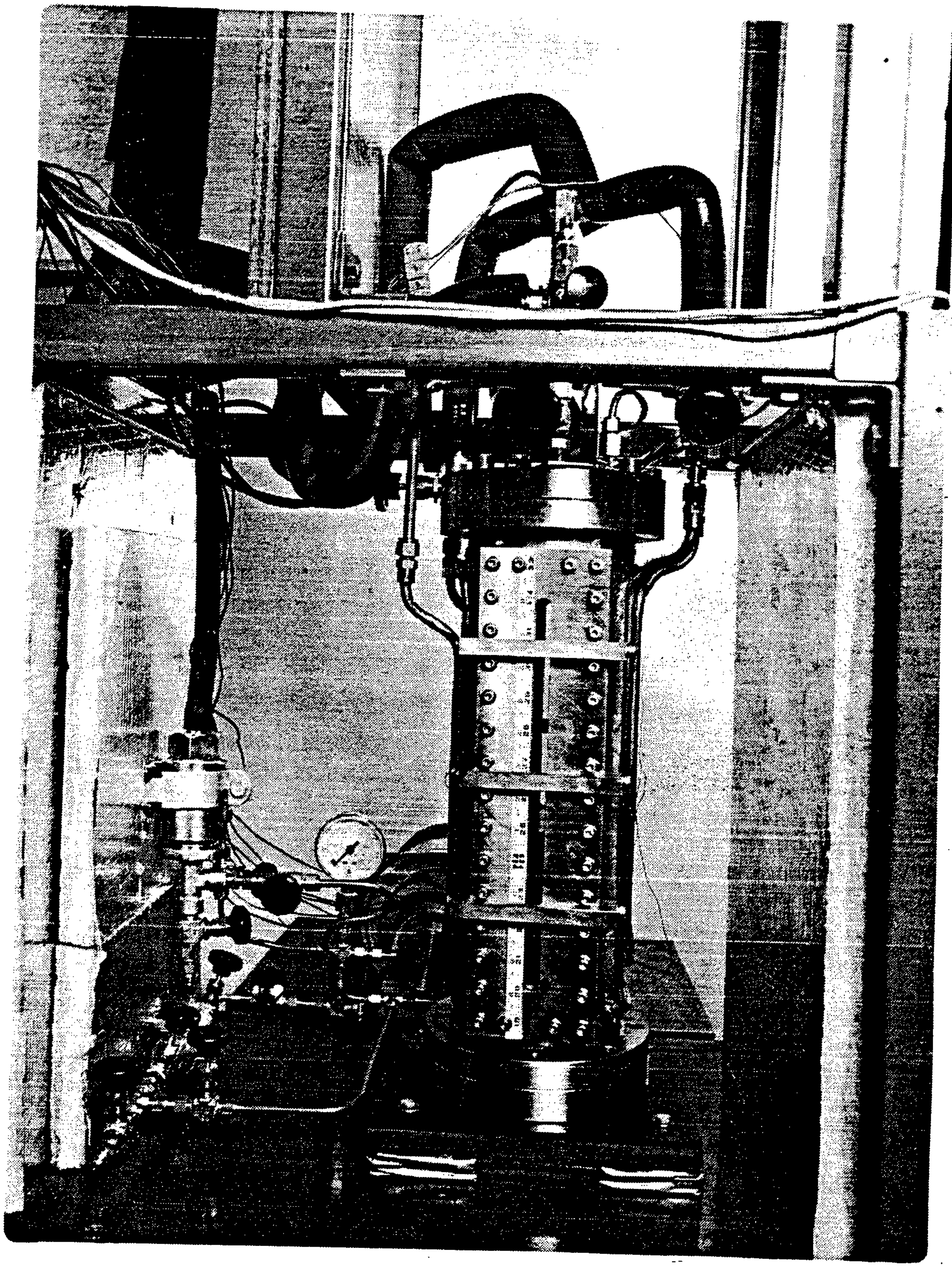

Figure 5.1 Lubricant/refrigerant test facility.

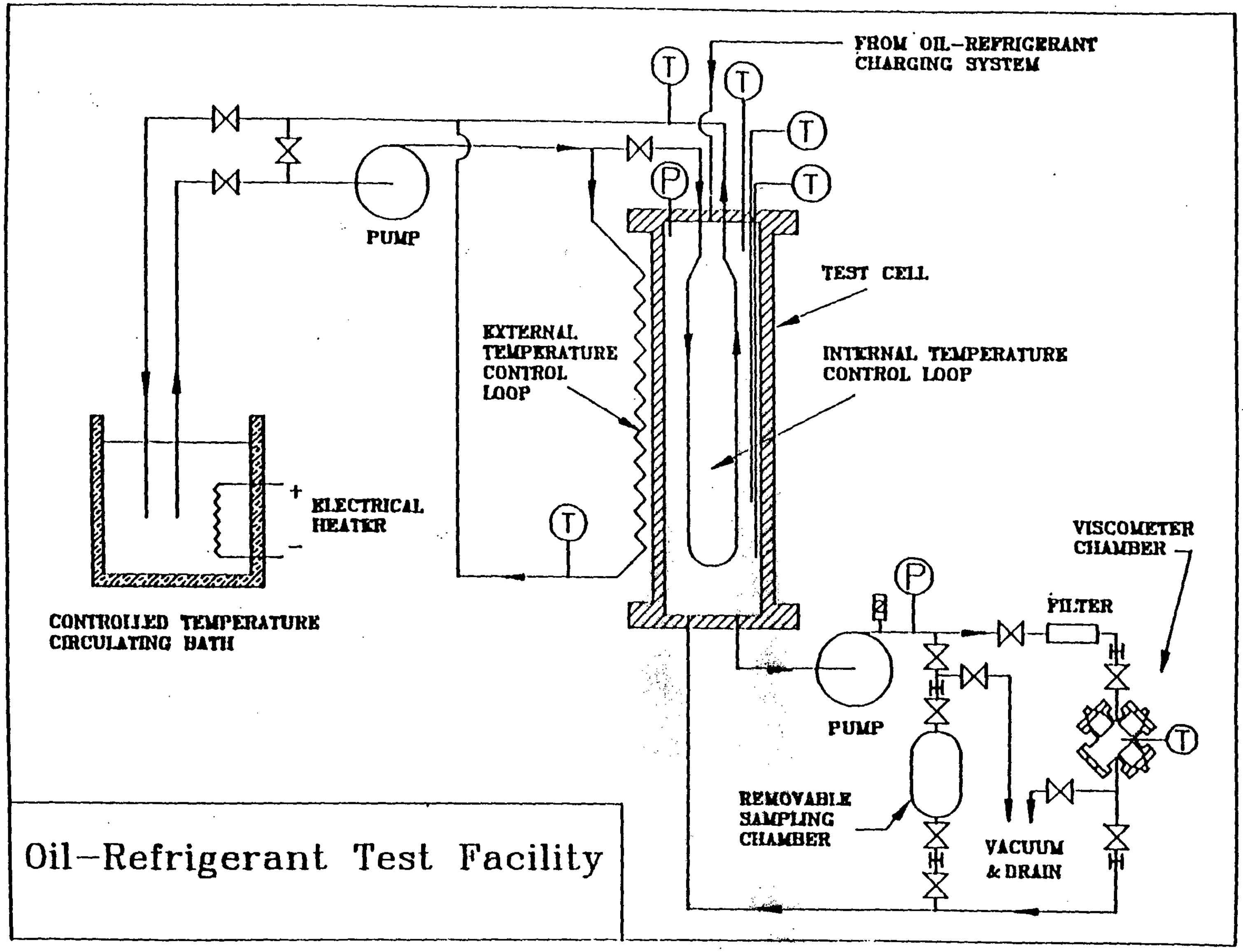

Figure 5.2 Lubricant/refrigerant test facility schematic.

interior portion splits into two loops to provide more thermal contact area. Each loop extends the length of the cell and is arranged so that it does not obstruct the view through the windows. A circulating bath with 3-kW heating element delivers the constant temperature fluid to the coils. The heating fluid is a poly-alpha-olefin (PAO), which performs well at higher temperatures in an open system because of its low viscosity and low volatility. Since the temperature of the heating fluid in the flow loop is held constant, the contents of the test cell eventually reach a steady-state condition. This condition is typically achieved from 2 to 3 hours after a 10°C (18°F) change in the circulating bath temperature.

Viscometer

Two viscosity sensors [Cambridge Applied Systems (CAS) 1989] are installed in an auxiliary viscometer loop. The operation of the viscosity sensor is based on an applied electro-magnetic field pulling a cylindrical piston through the fluid in a cylindrical cavity. The internal details are provided in the schematic drawing shown in Figure 5.3. The viscosity of the fluid is correlated with the time elapsed as the piston travels through a known distance. The associated electronics package provides a 0 to 2 volt d.c. signal correlated to viscosity. The uncertainty of the viscosity data is ±2.0% of the reading.

Each sensor also contains an RTD for measurement of the local temperature. This temperature is used in the reporting of the viscosity data. Dissipation of electrical energy in the drive coils of the sensor causes the fluid in the chamber to heat up. This internal self-heating in the viscometer causes the RTD reading to be somewhat higher than the temperatures indicated by the RTDs in the test cell during steady-state operation. This temperature difference is the highest at the lower end of the investigated temperature range. For example, at 40°C (104°F) the difference is about 3 - 4°C (5 - 7 °F), but this difference decreases to about zero at temperatures of 90°C (194°F) and beyond. This decrease to zero offset occurs as the heat losses to ambient become significant.

The viscosity sensors have viscosity ranges of 1-20 cp (centipoise) and 10-200 cp, respectively. These ranges overlap, therefore, some limited redundant measurements of viscosity are possible. This increases the confidence in the validity of the calibrations of each sensor. The operation of the sensor assumes the solutions to be "Newtonian" fluids, which is where the shear stress is proportional to the rate of deformation . Experience has shown that this assumption is reasonable. When these sensors operate in an equilibrium liquid mixture, internal self-heating in the drive coils of the viscometer tends to cause liquid to flash to vapor. These vapor bubbles formed proved to be very disruptive to stable and accurate operation of the viscometer. Therefore, it was necessary to construct an external flow loop through which compressed liquid could be pumped to the viscometer for measurement and then returned to the test cell. In this manner, liquid would not flash to vapor and stable viscosity readings for the liquid could be achieved. Pumping liquid from the test cell raises the pressure of the liquid without noticeably affecting the temperature. Also, a small increase in pressure has a negligible effect on liquid viscosity. Therefore, the pressurization provides a means of preventing vapor formation in the viscometer, while not perceptibly affecting the accuracy of the viscosity data.

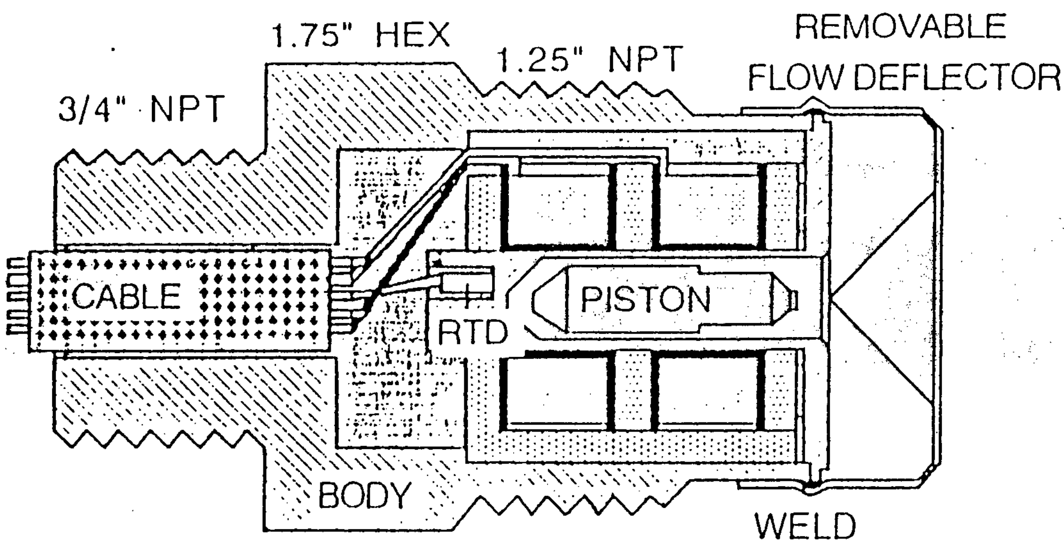

Figure 5.3 Viscosity-temperature sensor body (CAS 1989).

A magnetically driven positive-displacement gear pump with a variable-speed motor is used to move the fluid through the external viscosity flow loop and back to the test cell, as shown in Figures 5.1 and 5.2. Variable-speed control allows for adjustment of flow from almost zero to about 0.095 L/s (1.5 gpm). This provides the needed pressurization of the liquid in the loop while limiting uncontrolled heating of the fluid due to the addition of pumping energy.

A pressure gauge is installed in the loop to monitor the pressure increase. A valve is located immediately after the pressure gauge in the loop. This valve can be adjusted, along with the flow rate, to produce the required pump discharge pressure at a reasonable flow rate. Additionally, a filter is installed upstream of the viscometers to protect the viscometers from any dirt or debris that may have been introduced into the test cell.

The chamber that contains the viscometers is constructed from a 31.75-mm NPT [(1.25-in.) NPT] stainless steel pipe cross, where NPT stands for nominal pipe thread. Each of the viscosity sensors is threaded into a branch of the pipe cross, while the other branches are plugged for possible future use. Fluid enters the chamber through a fitting in the side of the pipe cross and flows around the active portion of the sensors before returning to the test cell through the 6.35-mm (0.25-in.) diameter return line. An RTD is also threaded into the side of the pipe cross to provide a check of the temperature. Valves are located at the inlet and exit of the chamber so that it may be isolated for disassembly. To allow removal of fluid after isolation of the chamber from the test cell, a vacuum/drain port is connected to the return line. This port also allows for the necessary evacuation of the chamber after reinstallation into the loop. The total volume of this external viscosity loop is 57.5 mL (3.51 in.^{3}), which is about 1.2% of the total system volume.

Sampling Loop

A sampling loop is connected in parallel with the viscosity loop. The sampling cylinder may be independently isolated and removed from the system for measurements of the liquid composition. The sampling loop is constructed from a 75-mL (4.6-in.^{3}) cylinder with two union bonnet valves on each side, as illustrated in Figure 5.2. When taking a sample, all four valves are closed to isolate the chamber from the rest of the system. The inner valves are closed to ensure that no fluid escapes from the sampling cylinder when it is removed. A vacuum/drain port is also provided to help in removal and reinstallation of the cylinder. The total volume of the sampling loop is 79 mL (4.8 in.^{3}). Disturbances of test cell conditions are minimized during sampling since the volume of the sampling loop is only 1.6% of the total system volume.

Equipment Enclosure

Although all components of the facility are insulated, a frame and panel enclosure was constructed to provide additional isolation from the room environment. The enclosure consists primarily of plywood, steel framing, and fiberglass ductboard, although, plexiglass viewports are included for the viewing of the test facility. The enclosure provides greater thermal uniformity and stability. It also provides a measure of protection to operators in the event of a high-pressure leak of the hot lubricant/refrigerant mixture. In addition, the enclosure allows accessibility and visibility for proper operation and monitoring.

Data Acquisition

Computerized data acquisition methods are used to obtain viscosities, temperatures, and pressures. A microcomputer, along with data acquisition hardware and software, provides a sufficient number of channels to monitor and record all signals generated by the installed sensors. A summary of the range and precision of the sensors is given in Table 5.1.

Two pressure transducers are in contact with the test cell contents via a port machined into the top plate. The pressure transducers employ a capacitance-sensing element. The pressure transducers were calibrated with the use of a deadweight pressure tester. These calibrations indicated that the output signals of both transducers are linear with pressure and that they match the factory calibrations. The pressure data uncertainty is ±3.24 kPa (0.47 psi). Five platinum RTDs independently track the temperature of the contents of the test facility. One monitors the test cell vapor space temperature. A second RTD is inserted into the pipe cross containing the viscometers, and the other three monitor the liquid temperature at various depths in the test cell. Thus, the liquid temperature is measured by four RTDs located in various places throughout the cell, and the liquid density data are reported at the average of these liquid temperatures.

Each RTD was connected with the required current transmitter, load resistor, and power supply and then calibrated. The current transmitters (signal conditioners) used with the RTDs linearize the response, providing a 4 to 20-mA signal that is linear over the temperature range -50°C (-58°F) to 150°C (302°F). This signal produces a 1- to 5-volt output when measured across a 250-ohm load resistor. This voltage output is then monitored by the data acquisition equipment. The calibration of output voltage vs. temperature showed that all of these RTDs provide a linear response. These temperature measurements have an uncertainty of ±0.1°C (0.2°F).

Refrigerant and Lubricant Charging

The charging of the refrigerant into the cell is achieved with the use of a piston and cylinder. The cylinder is used in the same manner as a syringe in that the refrigerant is drawn into the cylinder and then injected into the cell. The refrigerant is injected with the use of a stainless steel cylinder of 617.8 mL (37.7 in.^{3}) having a 50.8-mm (2-in.) bore with a 304.8-mm (12-in.) stroke. The cylinder displacements were calibrated with the use of R-113. The calibrated volume agrees with the above value to within ±2 mL (0.1 in.^{3}).

The presence of a "slug" charge of subcooled liquid refrigerant in the injection cylinder is checked by applying nitrogen pressure well above the vapor pressure of the refrigerant. If no rod movement is noticed, then there is no refrigerant vapor condensing in the cylinder. The cylinder is connected to the test cell with 6.35-mm (0.25-in.) diameter lines. With the application of the pressurized nitrogen gas to the rod side of the cylinder, the charging valve on the test cell is opened to allow the contents of the cylinder to be discharged. A scale is mounted directly behind the rod so that a partial injection of a given volume can be made. In other words, by determining in advance the required displacement, the charging can be stopped when the rod reaches the appropriate position.

The charging of lubricant to be tested can be performed in the same manner as the refrigerant, or the lubricant may be more conveniently drawn in while maintaining a vacuum in the test cell. The amount of lubricant can be weighed on a scale before being drawn in. Obviously, to charge lubricant in this manner, the test cell must not contain any refrigerant.

Summary

A versatile lubricant/refrigerant test facility has been described which can provide critically needed property data, especially at high pressures and temperatures, for a wide variety of lubricant/refrigerant mixtures. The facility incorporates a commercially available viscometer and windows for observation of the contents. The facility can be used for determination of the solubility, viscosity, and density of lubricant/refrigerant mixtures with refrigerant compositions ranging from 0 to 100%. Operating temperatures of the test facility range from 20°C (68°F) to 150°C (302°F). The operating pressure ranges from 0 to 3.5 MPa (0 to 500 psia). Viscosities from 1 cp to 200 cp can be measured. The sections that follow outline the experimental methods and provide experimental results for R-236ea/ISO68 pentaerythritol ester mixed-acid and R-114/ISO68 naphthenic mineral oil mixtures.

EXPERIMENTAL PROCEDURES AND DATA REDUCTION

In addition to constructing the test facility, procedures were developed for accurate and convenient measurement of the solubility, viscosity, and density of a wide range of lubricant/refrigerant solutions. This section provides a discussion of the experimental procedures that were employed to collect the data that will be presented in later sections.

General Experimental Procedures

The methods used to charge and operate the test facility depend upon the range of compositions and conditions desired in a particular test. A typical operating procedure for collecting data over a range of liquid-phase compositions involves several operations. These operations are described in more detail later. They include evacuating the test cell and auxiliary flow loops, injecting the necessary lubricant and refrigerant quantities, operating the gear pump to provide good mixing, heating the test cell and contents to the desired temperature, ensuring steady-state conditions, and taking the data. Cooling of the vessel contents to room temperature is then required in order to change the liquid concentration by injecting a known amount of refrigerant. The data acquisition system described earlier measures pressure, temperature, and viscosity automatically, while the liquid level height is measured manually. The recording of liquid level height at each test condition allows for the calculation of liquid density. This level reading also permits a calculation of the liquid composition, which varies slightly with temperature because of variations in the vapor and liquid densities. These topics will be explained more fully below.

Rig Cleansing

Prior to the injection of any fluid for testing, the test cell and auxiliary loops are rinsed several times with R-113 to remove traces of any lubricant that had previously been tested. After rinsing, if the vessel fails to hold a vacuum or set pressure, the o-rings that seal the windows may have to be replaced.

Data Measurement

After the connecting lines from the charging cylinder are attached to a valve on the test cell and these lines along with the cell and the auxiliary loops are evacuated, measured amounts of refrigerant and lubricant can be injected to provide a desired volume and concentration of liquid. Usually, the lubricant is charged first, and a pure lubricant "run" is completed. Specifically, data are obtained for the pure lubricant first, and then consecutive additions of refrigerant are possible. This method serves to remove the dissolved air and water from the lubricant since it is heated and evacuated during the first test. Also, the height of the test cell is sufficient to accommodate the addition of 40% (by mass) refrigerant to the initial lubricant charge. During the charging process, the circulating pump aids the mixing of the fluids. The contents are then heated to the desired maximum temperature and allowed to reach steady-state. The maximum temperature, during runs that contain refrigerant, is governed by the limiting test cell pressure of 3.5 MPa (500 psia). Once a steady-state condition has been reached, the temperature, pressure, viscosity, and height of the liquid-vapor interface are recorded. After all of the data are recorded, the contents are allowed to cool to the next desired test temperature. Data are collected at several steady-state test points during the cool-down phase. The pressure reported is the average of the pressures indicated by the two transducers. This solubility pressure is reported at a liquid-vapor interface temperature, which is the average of the temperature of the RTD in contact with vapor only and the average liquid temperature. The average liquid temperature is the mean of the temperatures indicated by the four RTDs immersed in the liquid in the test cell and in the pipe cross located in the flow loop containing the viscometers. The liquid density is reported at this average liquid temperature. The viscosity is reported at the temperature measured by an RTD inside the viscometer. As discussed previously, this temperature is generally slightly higher than the average liquid temperature due to the internal self-heating of the viscometer. Twenty consecutive viscosity readings are recorded and the mean and standard deviation are computed. The data are considered to be valid if the percentage standard deviation, defined as the standard deviation divided by the mean, is less than 1%.

Lubricant/Refrigerant Sample Evaluation

After the data for a given mixture have been collected over the desired temperature range and the test cell and contents have been returned to the room temperature, the sample cylinder is isolated and removed so that the mass fraction of refrigerant in the liquid can be determined. The procedure for determining the composition and liquid density of the lubricant/refrigerant mixture sample is discussed in the following paragraph.

After removal, the full sample cylinder is weighed, and then, one valve is cracked to transfer the refrigerant to a storage container. The cylinder is then heated, and the remaining refrigerant is evacuated so that the chamber now contains only lubricant. The chamber is weighed again. Next, using a suitable solvent, the lubricant is removed. Finally, the empty chamber is weighed so that the net weights of the lubricant, the refrigerant, and the mixture can be found by differences. The mixture composition can be calculated directly to an estimated uncertainty of $\pm$1%.

With the volume of the sampling chamber known, the mixture density can also be calculated. The temperature, pressure, and liquid level at which the sample was removed are also noted. These values allow for back-calculating the total masses of refrigerant and lubricant that are in the vessel. The total masses are then compared with the amounts originally injected. These values generally agree to within $\pm$1.5%. At this point, refrigerant may be added or removed to alter the concentration of the contents of the test cell so that another set of data can be obtained.

Mixture Concentration and Density Determination

During any particular run, the vapor mass varies as the temperature and pressure change, due to refrigerant vapor density changes. Also, as the temperature varies, the liquid density varies causing changes in the liquid and vapor volumes. For these reasons, the liquid concentration varies as the temperature and pressure change during any particular run. Generally, this variation in refrigerant concentration as temperature and pressure change during any particular test is less than 3%. Therefore, for the above reasons, the liquid density and composition must be calculated at each test condition. The following paragraphs explain these calculations in detail.

The test cell volume contains a vapor volume assumed to be composed of pure refrigerant and a liquid volume composed of a refrigerant-lubricant mixture. The relative volumes of each can be calculated through the measurement of the height of the corresponding liquid-vapor interface, which was previously correlated with the liquid volume. The total cell volume is known, so the vapor volume can also be calculated. Therefore, by noting the liquid level height at each test condition, the volumes of vapor and liquid are determined.

From the injection process and also from the sample calculations, the total mass of refrigerant and the total mass of the lubricant in the test cell are known. The vapor density can be obtained from the known vapor temperature and pressure vapor's volume. The vapor density is computed using a property routine based on work by National Institute of Standards and Technology [NIST (1993)]: however, any accurate property relation or table could be used. With the vapor density and the vapor volume, the mass of refrigerant in the vapor is calculated. The mass of refrigerant in the liquid is calculated by subtracting the mass of the refrigerant in the vapor from the total mass of refrigerant in the cell.

Finally, by dividing the mass of refrigerant in the liquid by the total liquid mass, the liquid composition at each test condition can be calculated. Also, since the volume and mass of the liquid is known, the liquid density can be calculated for each test point. It should be noted that the densities and compositions are not calculated by using the ideal mixing assumption, but, rather, they are determined from test data. As described earlier, a liquid sample is taken at one temperature during each run to check the composition and mixture density.

Data Reduction

In addition to the calculations of the liquid composition and density, correlating equations that fit the data were derived. These correlating equations fit pressure, density, and viscosity as functions of temperature and liquid composition. As discussed previously, the pressure, viscosity, temperature, and liquid level are measured for each test point. From these data, calculations are performed to determine the liquid density and composition at each test condition. This procedure was presented in a previous section during a discussion of experimental procedures. A detailed example of these calculations and the associated uncertainties are provided in a publication by VanGaalen et al. (1991a, 1991b).

Once the composition and density are determined for each data point, the data set consists of the viscosity, pressure, and density for combinations of the liquid composition and temperature. A useful and convenient presentation of these results can be made through the development of correlating equations for viscosity, pressure, and density as functions of composition and temperature. A discussion of the techniques which were used to derive coefficients for the empirical correlating equations is presented in the following section.

Data Correlation Technique

After all the data have been collected and reduced, it is gathered into one file so that a nonlinear regression analysis may be performed. Thus, equations for viscosity, pressure, and density as functions of temperature and concentration can be obtained. These equations can be used to reproduce the data, graphically plot results, or interpolate results at intermediate states for which data were not directly obtained.

The linear regression analysis is performed using Statistical Analysis and System [SAS (1993)] to determine the set of coefficients for the following empirical equations.

$$\log_{10} \mu^* = A_0 + A_1 C + A_{2\_} + A_3 CT^* + A_4 C^2 + A_5 C^2 T^* + A_6 CT^{*2} + A_7 T^{*2} + A_8 C^2 T^{*2} \quad (1)$$

$$P = B_0 + B_1 C + B_2 T^* + B_3 CT^* + B_4 C^2 + B_5 C^2 T^* + B_6 C\_^2 + B_7 T^{*2} + B_8 C^2 T^{*2} \quad (2)$$

$$\rho = D_0 + D_1 C + D_2 T^* + D_3 CT^* + D_4 C^2 + D_5 C^2 T^* + D_6 CT^{*2} + D_7 T^{*2} + D_8 C^2 T^{*2} \quad (3)$$

where

A_i, B_i, D_i = set of coefficients in Eqs. 1-3 (units vary depending on term)

μ^* = nondimensional absolute viscosity (viscosity in centipoise divided by one centipoise)

P = the absolute pressure, MPa,

ρ = the density of the liquid, g/mL,

C = mass fraction of refrigerant in the liquid, and

T^* = nondimensional temperature (temperature in K divided by a reference temperature of 293.15K).

The above equations are nonlinear, but they are linearized using the following variable substitutions.

$X_1 = C$;	$X_2 = T^*$;	$X_3 = CT^*$;	$X_4 = C^2$;
$X_5 = C^2T^*$;	$X_6 = CT^{*2}$;	$X_7 = T^{*2}$;	$X_8 = C^2T^{*2}$

After these substitutions, the equations are linear in the eight variables X_1 through X_8. For example,

$$P = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4 + B_5X_5 + B_6X_6 + B_7X_7 + B_8X_8 \quad (4)$$

The resulting equations are empirical fits of the data, and are not based on theoretical considerations. Also, some of the coefficients do not significantly contribute to the correlation. SAS provides statistical information about the significance of each of the coefficients in the above equations and calculates regression coefficients as an indication of the overall goodness-of-fit of each equation.

Summary

The operation of the lubricant/refrigerant test facility has been described in detail. Experimental procedures and data reduction techniques, including the correlating equations, have been outlined. Data obtained with this test facility for R-236ea/ISO68 pentaerythritol ester mixed-acid and R-114/ISO68 naphthenic mineral oil mixtures are presented in the following sections.

REFRIGERANT/LUBRICANT SOLUTION PROPERTY RESULTS

This section presents results of solubility, viscosity, and density measurements for R-236ea/ISO68 pentaerythritol ester mixed-acid and R-114/ISO68 naphthenic mineral oil mixtures. First, some characteristics of the test lubricants are presented and the experimental data are discussed. Then, the results of the regression analysis are given in the form of coefficients for empirical equations. The correlations are then presented graphically and in tabular form. A complete list of the experimental data is also tabulated.

Lubricant Characteristics

Table 5.1 shows some properties of the two lubricants. The base fluid for each lubricant is given along with the density and viscosity at various temperatures. The flash and pour points are also listed.

TABLE 5.1: TEST LUBRICANT PROPERTIES

Lubricant (Viscosity) trade name	Kinematic Viscosity (cSt)	Density (g/mL)	Pour Point (°C)	Flash Point (°C)
naphthenic mineral oil (ISO68) York C	62.5@37.8°C 6.04@98.9°C	0.916@ 20°C	-34.4	179
pentaerythritol ester mixed-acid (ISO68) Castrol SW68	68.0@40°C 8.8@100°C	0.980@ 20°C	-39	250

Results and Discussion

Results of the measurements for R-236ea/ISO68 pentaerythritol ester mixed-acid and R-114/ISO68 naphthenic mineral oil mixtures are presented below. For each lubricant/refrigerant combination investigated, the data set at each nominal liquid composition consists of temperature, pressure, composition, absolute viscosity, and density. These data for each of the nominal concentration tests are then compiled in one file to complete the data set for each lubricant/refrigerant pair. As described previously, a nonlinear regression analysis is performed on this data set to find the best set of coefficients of the correlating equations. It should be emphasized that the correlating equations are empirical fits of the data and are not based on theoretical considerations. The results of this regression are then provided graphically as well as in the form of the empirical correlations.

Raw Data

Tables 5.2 through 5.4 provide raw experimental data for R-236ea/ISO68 pentaerythritol ester mixed-acid mixtures. Table 5.2 tabulates vapor pressure versus temperature for various liquid compositions. Tables 5.3 and

5.4 provide density and viscosity data, respectively, as a function of temperature and liquid composition. Three separate tables are required since the vapor pressure, density and viscosity are reported at slightly different temperatures, as was discussed previously. Tables 5.5 through 5.7 provide raw experimental data for R-114/ ISO68 naphthenic mineral oil mixtures.

The data in Tables 5.2 and 5.5 show that for a nominal concentration the vapor pressure increases with temperature. Also, the data demonstrate that the vapor pressure increases as the refrigerant concentration is increased. The data in Tables 5.3 and 5.6 show that for a nominal concentration the liquid density decreases with temperature. Also, the data demonstrate that the density increases as the refrigerant concentration is increased, with the reason being that the pure refrigerant density is greater than the pure lubricant density. The data in Tables 5.4 and 5.7 show that for a nominal concentration the viscosity decreases with temperature. Also, the data demonstrate that the viscosity decreases as the refrigerant concentration is increased.

TABLE 5.2: RAW SOLUBILITY DATA FOR R-236ea/ISO68 PENTAERYTHRITOL ESTER MIXED-ACID MIXTURES

Temp.[a] (°C)	Pressure[a] (psia)	Concentration[b] (mass frac. ref.)
29.07	0.00	0.000
47.61	0.00	0.000
22.62	0.00	0.000
42.02	0.00	0.000
50.98	0.00	0.000
64.41	0.00	0.000
77.09	0.00	0.000
77.09	0.00	0.000
89.61	0.00	0.000
106.77	0.00	0.000
106.77	0.00	0.000
54.93	0.00	0.000
54.93	0.00	0.000
67.43	0.00	0.000
67.44	0.00	0.000
79.11	0.00	0.000
79.13	0.00	0.000
77.60	0.00	0.000
93.43	0.00	0.000
93.57	0.00	0.000
102.13	0.00	0.000
102.12	0.00	0.000
31.13	8.53	0.104
22.43	6.84	0.105
56.32	16.86	0.102

Temp. (°C)	Pressure (psia)	Concentration (mass frac. ref.)
68.93	22.89	0.101
82.50	30.99	0.099
96.31	40.91	0.097
109.35	51.48	0.095
28.84	17.79	0.268
29.14	17.98	0.268
21.69	14.03	0.269
42.71	26.97	0.267
54.99	38.18	0.265
67.62	52.39	0.263
81.44	72.30	0.260
94.38	95.16	0.257
109.78	127.37	0.253
21.09	20.47	0.451
22.92	21.70	0.451
38.38	36.08	0.450
44.83	42.79	0.450
56.04	58.72	0.449
68.78	81.74	0.448
81.69	111.15	0.447
96.01	152.48	0.445
109.63	202.02	0.443
87.71	133.13	0.445
107.05	200.67	0.442

[a]Pressure sensors were read in English units of psia while temperature sensors were read in SI units of °C.
[b]Concentration is defined as the mass of refrigerant present divided by the mass of the lubricant/refrigerant mixture.

TABLE 5.3: RAW DENSITY DATA FOR R-236ea/ISO68 PENTAERYTHRITOL ESTER MIXED-ACID MIXTURES

Temperature (°C)	Density (g/mL)	Concentration[a] (mass frac. ref.)	Vapor Density (g/mL)
31.67	0.966	0.000	0.000
48.25	0.955	0.000	0.000
26.75	0.970	0.000	0.000
43.84	0.958	0.000	0.000
51.75	0.959	0.000	0.000
63.97	0.944	0.000	0.000
75.91	0.936	0.000	0.000
75.90	0.936	0.000	0.000
87.89	0.929	0.000	0.000
104.59	0.918	0.000	0.000
104.59	0.918	0.000	0.000
55.10	0.951	0.000	0.000
55.10	0.951	0.000	0.000
66.74	0.943	0.000	0.000
66.76	0.943	0.000	0.000
77.95	0.936	0.000	0.000
77.94	0.936	0.000	0.000
75.69	0.937	0.000	0.000
90.63	0.927	0.000	0.000
90.75	0.927	0.000	0.000
99.74	0.921	0.000	0.000
99.73	0.921	0.000	0.000
32.99	1.004	0.104	0.004
25.63	1.010	0.105	0.003
56.26	0.986	0.102	0.007
68.01	0.976	0.101	0.009
80.92	0.964	0.099	0.011
94.15	0.955	0.097	0.015
106.41	0.945	0.095	0.018
30.29	1.062	0.268	0.008
30.62	1.062	0.268	0.008
23.96	1.068	0.269	0.006
43.34	1.049	0.267	0.011
54.98	1.039	0.265	0.016
66.75	1.028	0.263	0.021
80.00	1.015	0.260	0.028
92.25	1.003	0.257	0.036
107.03	0.989	0.253	0.048
22.33	1.145	0.451	0.009
24.52	1.143	0.451	0.010
39.66	1.129	0.450	0.016
44.82	1.120	0.450	0.019
55.57	1.108	0.449	0.025

(continued)

Table 5.3 (continued)

Temperature (°C)	Density (g/mL)	Concentration (mass frac. ref.)	Vapor Density (g/mL)
67.93	1.093	0.448	0.034
80.44	1.076	0.447	0.046
94.44	1.058	0.445	0.064
107.57	1.041	0.443	0.085
84.04	1.061	0.445	0.055
102.27	1.037	0.442	0.084

[a]Concentration is defined as the mass of refrigerant present divided by the mass of the lubricant/refrigerant mixture.

TABLE 5.4: RAW VISCOSITY DATA FOR R-236ea/ISO68 PENTAERYTHRITOL ESTER MIXED-ACID MIXTURES

Temperature (°C)	Absolute Viscosity (cP)	Concentration[a] (mass frac. ref.)
37.04	74.85	0.000
49.78	39.99	0.000
33.86	8.89	0.000
47.85	43.85	0.000
52.67	35.17	0.000
64.72	21.53	0.000
75.17	14.69	0.000
75.17	14.67	0.000
87.06	10.72	0.000
102.84	6.92	0.000
102.84	6.91	0.000
56.49	29.84	0.000
56.50	29.83	0.000
67.42	19.66	0.000
67.42	19.61	0.000
75.42	14.78	0.000
77.64	14.01	0.000
75.18	15.17	0.000
90.29	9.59	0.000
90.41	9.57	0.000
98.55	7.70	0.000
98.54	7.69	0.000
36.80	38.85	0.104
30.98	51.94	0.105
57.57	15.99	0.102
68.47	12.04	0.101

(continued)

Table 5.4 (continued)

Temperature (°C)	Absolute Viscosity (cP)	Concentration (mass frac. ref.)
78.89	8.51	0.099
92.61	6.02	0.097
103.57	4.64	0.095
35.55	17.16	0.268
36.03	16.85	0.268
30.25	21.17	0.269
46.61	11.54	0.267
56.85	8.25	0.265
65.87	6.40	0.263
78.35	4.52	0.260
89.36	3.45	0.257
102.71	2.57	0.253
27.91	7.70	0.451
30.28	7.13	0.451
42.49	5.06	0.450
48.29	4.16	0.450
56.04	3.42	0.449
66.67	2.61	0.448
78.09	2.09	0.447
89.28	1.73	0.445
102.49	1.30	0.443
73.09	2.62	0.445
85.86	2.14	0.442

[a]Concentration is defined as the mass of refrigerant present divided by the mass of the lubricant/refrigerant mixture.

TABLE 5.5: RAW SOLUBILITY DATA FOR R-114/ISO68 NAPHTHENIC MINERAL OIL MIXTURES

Temperature (°C)[a]	Pressure (psia)	Concentration[a] (mass frac. ref.)
19.88	0.00	0.000
21.03	0.00	0.000
23.50	0.00	0.000
29.82	0.00	0.000
40.26	0.00	0.000
50.65	0.00	0.000
62.09	0.00	0.000
61.40	0.00	0.000
73.71	0.00	0.000
82.54	0.00	0.000
98.45	0.00	0.000
22.39	20.31	0.165
24.86	21.82	0.165
33.05	25.65	0.164
44.58	32.86	0.162
56.33	44.38	0.160
68.38	54.76	0.158
78.79	62.02	0.157
88.94	70.97	0.156
103.18	88.08	0.153
27.18	31.34	0.293
19.89	26.24	0.293
43.20	45.50	0.291
55.53	59.14	0.289
66.71	73.76	0.287
77.97	90.98	0.285
86.17	104.40	0.284
102.71	138.28	0.280
30.93	43.17	0.449
20.59	33.52	0.450
47.10	62.13	0.448
58.70	79.41	0.448
68.83	97.63	0.447
82.29	126.88	0.446
95.69	163.79	0.445

[a]Concentration is defined as the mass of refrigerant present divided by the mass of the lubricant/refrigerant mixture.

TABLE 5.6: RAW DENSITY DATA FOR R-114/ISO68 NAPHTHENIC MINERAL OIL MIXTURES

Temperature (°C)	Density (g/mL)	Concentration[a] (mass frac. ref.)	Vapor Density[b] (g/mL)
21.99	0.912	0.000	0.000
23.06	0.912	0.000	0.000
26.33	0.909	0.000	0.000
32.15	0.907	0.000	0.000
41.06	0.900	0.000	0.000
50.46	0.895	0.000	0.000
60.92	0.888	0.000	0.000
60.51	0.889	0.000	0.000
71.68	0.882	0.000	0.000
80.16	0.877	0.000	0.000
96.10	0.867	0.000	0.000
25.06	0.976	0.165	0.010
27.20	0.974	0.165	0.011
34.22	0.969	0.164	0.013
45.05	0.961	0.162	0.016
56.04	0.953	0.160	0.021
67.37	0.944	0.158	0.025
77.01	0.937	0.157	0.027
86.26	0.930	0.156	0.030
100.34	0.920	0.153	0.037
28.01	1.026	0.293	0.016
21.03	1.032	0.293	0.014
43.46	1.014	0.291	0.023
55.19	1.004	0.289	0.029
65.74	0.995	0.287	0.035
76.45	0.985	0.285	0.042
83.94	0.979	0.284	0.048
100.46	0.963	0.280	0.062
31.23	1.098	0.449	0.022
21.24	1.109	0.450	0.017
46.93	1.082	0.448	0.031
58.09	1.070	0.448	0.040
67.86	1.060	0.447	0.048
80.95	1.050	0.446	0.062
94.16	1.017	0.445	0.081

[a]Concentration is defined as the mass of refrigerant present divided by the mass of the lubricant/refrigerant mixture.
[b]Refrigerant or R-114.

TABLE 5.7: RAW VISCOSITY DATA FOR R-114/ISO68 NAPHTHENIC MINERAL OIL MIXTURES

Temperature (°C)	Absolute Viscosity (cP)	Concentration[a] (mass frac. ref.)
27.60	104.70	0.000
29.15	94.38	0.000
31.78	79.66	0.000
35.79	61.94	0.000
43.83	39.07	0.000
51.99	25.58	0.000
62.08	16.23	0.000
61.93	16.51	0.000
72.68	11.11	0.000
80.10	8.60	0.000
95.89	5.44	0.000
28.67	27.76	0.165
31.21	24.60	0.165
37.84	18.07	0.164
47.73	12.15	0.162
57.98	8.53	0.160
68.66	6.18	0.158
77.87	4.78	0.157
86.42	3.84	0.156
100.01	2.83	0.153
32.56	10.24	0.293
26.47	13.05	0.293
46.16	6.46	0.291
57.04	4.69	0.289
67.03	3.61	0.287
77.10	2.87	0.285
84.13	2.46	0.284
100.10	1.78	0.280
35.20	4.43	0.449
26.27	5.81	0.450
49.91	3.05	0.448
60.36	2.34	0.448
68.99	1.96	0.447
81.54	1.52	0.446
93.70	1.20	0.445

[a]Concentration is defined as the mass of refrigerant present divided by the mass of the lubricant/refrigerant mixture.

Correlating Equations

The coefficients for the correlating equations (Eqs. 1 through 3), as derived for R-236ea/ISO68 pentaerythritol ester mixed-acid mixtures, are given in Table 5.8. It should be noted that when using the correlations in lieu of the graphs care must be taken to avoid extrapolation beyond the limits of applicability. These limits of applicability are given along with the coefficients in Table 5.8. The coefficients for the correlating equations, as derived for R-114/ ISO68 naphthenic mineral oil mixtures, are given in Table 5.9.

TABLE 5.8: COEFFICIENTS TO THE CORRELATING EQUATIONS FOR R-236EA/ISO68 PENTAERYTHRITOL ESTER MIXED-ACID MIXTURES

Term	Viscosity	Pressure	Density
Intercept	A_0 = 17.6225	B_0 = 0.0	D_0 = 1.1766
C	A_1 = -19.7445	B_1 = 27.6499	D_1 = 0.36572
T*	A_2 = -23.4289	B_2 = 0.0	D_2 = -0.20101
CT*	A_3 = 26.9284	B_3 = -56.6801	D_3 = 0.0
C_2	A_4 = 0.0	B_4 = -9.6043	D_4 = 0.0
C_2T^*	A_5 = 0.0	B_5 = 20.2567	D_5 = 0.64247
CT^*_2	A_6 = -10.0516	B_6 = 29.4792	D_6 = -0.04168
T^*_2	A_7 = 8.0674	B_7 = 0.0	D_7 = 0.0
$C_2T^*_2$	A_8 = 0.13801	B_8 = -10.9266	D_8 = -0.51191

Note: The limits of applicability of the correlating equations (Eqs. 1 through 3) are:
Concentration (X): 0 to 50% refrigerant
Temperature: 20°C to 100°C (68°F to 212°F)
Pressure: 0 to 1.4 MPa (0 to 200 psia)

TABLE 5.9: COEFFICIENTS TO THE CORRELATING EQUATIONS FOR R-114/ISO68 NAPHTHENIC MINERAL OIL MIXTURES

Term	Viscosity	Pressure	Density
Intercept	$A_0 = 22.6390$	$B_0 = 0.0$	$D_0 = 1.0900$
C	$A_1 = -51.3833$	$B_1 = 13.0045$	$D_1 = 0.36493$
T^*	$A_2 = -32.0444$	$B_2 = 0.0$	$D_2 = -0.17660$
CT^*	$A_3 = 77.4782$	$B_3 = -31.1820$	$D_3 = 0.0$
C_2	$A_4 = 42.6780$	$B_4 = 8.5821$	$D_4 = -2.0077$
C_2T^*	$A_5 = -66.8882$	$B_5 = -9.4839$	$D_5 = 4.4864$
CT^*_2	$A_6 = -30.2322$	$B_6 = 19.0693$	$D_6 = 0.0$
T^*_2	$A_7 = 11.6399$	$B_7 = 0.0$	$D_7 = 0.0$
$C_2T^*_2$	$A_8 = 26.5244$	$B_8 = 0.0$	$D_8 = -2.3293$

Note: The limits of applicability of the correlating equations (Eqs. 1 through 3) are:
Concentration (X): 0 to 50% refrigerant
Temperature: 20°C to 100°C (68°F to 212°F)
Pressure: 0 to 1.4 MPa (0 to 200 psia)

Tabular Results

With the use of the above correlating equations, charts of solubility, viscosity, and density can be produced. These "smoothed data" are sometimes (such as when using a computer) more useful than picking numbers off of graphs. Tables 5.10 and 5.11, along with Tables 5.12 and 5.13, provide "smoothed data" for R-236ea/ISO68 pentaerythritol ester mixed-acid and R-114/ISO68 naphthenic mineral oil mixtures, respectively. By inspection of the data in the tables, the same trends as identified in the raw data can be observed.

TABLE 5.10: SMOOTHED DATA FOR R-236ea/ISO68 PENTAERYTHRITOL ESTER MIXED-ACID MIXTURES: CONSTANT TEMPERATURE

Temp.	Lubricant	Density	Viscosity			Pressure	
(°C)	(mass frac.)	(g/mL)	(cP)	(cSt)	(SUS)	(MPa)	(psia)
30.0	0.000	0.969	104.84	108.23	501.1	0.0000	0.00
30.0	0.050	0.985	77.36	78.53	363.8	0.0272	3.94
30.0	0.100	1.002	57.18	57.06	264.8	0.0527	7.64
30.0	0.150	1.020	42.33	41.52	193.5	0.0765	11.09
30.0	0.200	1.038	31.39	30.26	142.5	0.0986	14.29
30.0	0.250	1.056	23.32	22.08	106.6	0.1189	17.25
30.0	0.300	1.076	17.36	16.14	81.8	0.1376	19.96
30.0	0.350	1.095	12.94	11.81	65.2	0.1546	22.42
30.0	0.400	1.116	9.66	8.66	54.2	0.1698	24.63
30.0	0.450	1.137	7.23	6.36	46.7	0.1834	26.59
30.0	0.500	1.159	5.41	4.67	41.3	0.1952	28.31
40.0	0.000	0.962	63.07	65.57	304.4	0.0000	0.00
40.0	0.050	0.978	47.61	48.68	226.6	0.0360	5.22
40.0	0.100	0.995	36.01	36.20	169.5	0.0698	10.13
40.0	0.150	1.012	27.28	26.96	128.0	0.1015	14.72
40.0	0.200	1.030	20.71	20.11	98.3	0.1310	19.00
40.0	0.250	1.048	15.74	15.03	77.5	0.1583	22.96
40.0	0.300	1.067	11.99	11.25	63.3	0.1834	26.61
40.0	0.350	1.086	9.15	8.43	53.5	0.2064	29.94
40.0	0.400	1.105	7.00	6.33	46.6	0.2272	32.96
40.0	0.450	1.126	5.36	4.76	41.6	0.2459	35.66
40.0	0.500	1.146	4.11	3.59	37.9	0.2624	38.05
50.0	0.000	0.955	39.62	41.49	193.8	0.0000	0.00
50.0	0.050	0.971	30.52	31.43	148.1	0.0482	6.99
50.0	0.100	0.987	23.55	23.85	114.5	0.0936	13.57
50.0	0.150	1.004	18.21	18.13	90.2	0.1362	19.76
50.0	0.200	1.021	14.11	13.81	72.9	0.1761	25.54
50.0	0.250	1.039	10.95	10.54	60.8	0.2132	30.93
50.0	0.300	1.057	8.52	8.05	52.3	0.2476	35.91
50.0	0.350	1.076	6.64	6.17	46.2	0.2792	40.49
50.0	0.400	1.095	5.18	4.73	41.6	0.3080	44.68
50.0	0.450	1.114	4.05	3.64	38.1	0.3341	48.46
50.0	0.500	1.134	3.18	2.80	35.3	0.3575	51.84
60.0	0.000	0.948	25.99	27.41	130.3	0.0000	0.00
60.0	0.050	0.964	20.37	21.13	102.9	0.0637	9.24
60.0	0.100	0.980	16.00	16.32	82.9	0.1239	17.97
60.0	0.150	0.996	12.59	12.64	68.5	0.1807	26.20
60.0	0.200	1.013	9.93	9.80	58.3	0.2339	33.93
60.0	0.250	1.030	7.85	7.61	50.9	0.2837	41.15
60.0	0.300	1.048	6.21	5.93	45.5	0.3300	47.87
60.0	0.350	1.066	4.93	4.63	41.3	0.3729	54.08
60.0	0.400	1.084	3.92	3.62	38.1	0.4122	59.79
60.0	0.450	1.102	3.12	2.83	35.5	0.4481	64.99

(continued)

Table 5.10 (continued)

Temp. (°C)	Lubricant (mass frac.)	Density (g/mL)	Viscosity (cP)	Viscosity (cSt)	Viscosity (SUS)	Pressure (MPa)	Pressure (psia)
60.0	0.500	1.121	2.49	2.22	33.4	0.4805	69.69
70.0	0.000	0.941	17.80	18.91	93.6	0.0000	0.00
70.0	0.050	0.957	14.16	14.80	76.9	0.0826	11.98
70.0	0.100	0.973	11.29	11.60	64.8	0.1609	23.33
70.0	0.150	0.989	9.02	9.12	56.0	0.2348	34.06
70.0	0.200	1.005	7.22	7.18	49.6	0.3045	44.16
70.0	0.250	1.022	5.79	5.67	44.7	0.3698	53.63
70.0	0.300	1.038	4.66	4.49	40.9	0.4308	62.48
70.0	0.350	1.056	3.75	3.56	37.9	0.4874	70.69
70.0	0.400	1.073	3.03	2.83	35.5	0.5398	78.29
70.0	0.450	1.090	2.45	2.25	33.6	0.5878	85.25
70.0	0.500	1.108	1.99	1.80	32.0	0.6315	91.59
80.0	0.000	0.934	12.73	13.62	72.4	0.0000	0.00
80.0	0.050	0.950	10.25	10.79	61.9	0.1049	15.21
80.0	0.100	0.965	8.27	8.57	54.2	0.2044	29.65
80.0	0.150	0.981	6.69	6.82	48.4	0.2987	43.32
80.0	0.200	0.997	5.42	5.44	44.0	0.3877	56.23
80.0	0.250	1.013	4.41	4.35	40.5	0.4714	68.37
80.0	0.300	1.029	3.59	3.49	37.7	0.5498	79.74
80.0	0.350	1.045	2.93	2.80	35.5	0.6229	90.34
80.0	0.400	1.062	2.40	2.26	33.6	0.6907	100.18
80.0	0.450	1.078	1.97	1.82	32.1	0.7532	109.24
80.0	0.500	1.095	1.62	1.48	30.9	0.8104	117.54
90.0	0.000	0.928	9.51	10.25	60.0	0.0000	0.00
90.0	0.050	0.943	7.73	8.19	53.0	0.1305	18.93
90.0	0.100	0.958	6.29	6.57	47.7	0.2546	36.93
90.0	0.150	0.973	5.14	5.28	43.5	0.3723	54.00
90.0	0.200	0.988	4.21	4.26	40.3	0.4836	70.14
90.0	0.250	1.004	3.45	3.44	37.6	0.5886	85.36
90.0	0.300	1.019	2.84	2.79	35.4	0.6871	99.65
90.0	0.350	1.034	2.34	2.26	33.7	0.7792	113.02
90.0	0.400	1.050	1.94	1.84	32.3	0.8650	125.45
90.0	0.450	1.065	1.60	1.51	31.1	0.9443	136.96
90.0	0.500	1.081	1.33	1.23	30.1	1.0173	147.55
100.0	0.000	0.921	7.41	8.05	52.6	0.0000	0.00
100.0	0.050	0.936	6.06	6.48	47.4	0.1595	23.13
100.0	0.100	0.950	4.97	5.23	43.4	0.3114	45.16
100.0	0.150	0.965	4.09	4.24	40.2	0.4556	66.08
100.0	0.200	0.980	3.37	3.44	37.6	0.5923	85.90
100.0	0.250	0.995	2.79	2.80	35.5	0.7213	104.61
100.0	0.300	1.009	2.31	2.29	33.8	0.8427	122.22
100.0	0.350	1.024	1.92	1.87	32.4	0.9565	138.73
100.0	0.400	1.038	1.60	1.54	31.2	1.0626	154.12
100.0	0.450	1.053	1.33	1.27	30.3	1.1612	168.42
100.0	0.500	1.067	1.12	1.05	29.5	1.2521	181.61

TABLE 5.11: SMOOTHED DATA FOR R-236ea/ISO68 PENTAERYTHRITOL ESTER MIXED-ACID MIXTURES: CONSTANT CONCENTRATION

Temp.	Lubricant	Density	Viscosity			Pressure	
(°C)	(mass frac.)	(g/mL)	(cP)	(cSt)	(SUS)	(MPa)	(psia)
30.0	0.000	0.969	104.84	108.23	501.1	0.0000	0.00
40.0	0.000	0.962	63.07	65.57	304.4	0.0000	0.00
50.0	0.000	0.955	39.62	41.49	193.8	0.0000	0.00
60.0	0.000	0.948	25.99	27.41	130.3	0.0000	0.00
70.0	0.000	0.941	17.80	18.91	93.6	0.0000	0.00
80.0	0.000	0.934	12.73	13.62	72.4	0.0000	0.00
90.0	0.000	0.928	9.51	10.25	60.0	0.0000	0.00
100.0	0.000	0.921	7.41	8.05	52.6	0.0000	0.00
30.0	0.050	0.985	77.36	78.53	363.8	0.0272	3.94
40.0	0.050	0.978	47.61	48.68	226.6	0.0360	5.22
50.0	0.050	0.971	30.52	31.43	148.1	0.0482	6.99
60.0	0.050	0.964	20.37	21.13	102.9	0.0637	9.24
70.0	0.050	0.957	14.16	14.80	76.9	0.0826	11.98
80.0	0.050	0.950	10.25	10.79	61.9	0.1049	15.21
90.0	0.050	0.943	7.73	8.19	53.0	0.1305	18.93
100.0	0.050	0.936	6.06	6.48	47.4	0.1595	23.13
30.0	0.100	1.002	57.18	57.06	264.8	0.0527	7.64
40.0	0.100	0.995	36.01	36.20	169.5	0.0698	10.13
50.0	0.100	0.987	23.55	23.85	114.5	0.0936	13.57
60.0	0.100	0.980	16.00	16.32	82.9	0.1239	17.97
70.0	0.100	0.973	11.29	11.60	64.8	0.1609	23.33
80.0	0.100	0.965	8.27	8.57	54.2	0.2044	29.65
90.0	0.100	0.958	6.29	6.57	47.7	0.2546	36.93
100.0	0.100	0.950	4.97	5.23	43.4	0.3114	45.16
30.0	0.150	1.020	42.33	41.52	193.5	0.0765	11.09
40.0	0.150	1.012	27.28	26.96	128.0	0.1015	14.72
50.0	0.150	1.004	18.21	18.13	90.2	0.1362	19.76
60.0	0.150	0.996	12.59	12.64	68.5	0.1807	26.20
70.0	0.150	0.989	9.02	9.12	56.0	0.2348	34.06
80.0	0.150	0.981	6.69	6.82	48.4	0.2987	43.32
90.0	0.150	0.973	5.14	5.28	43.5	0.3723	54.00
100.0	0.150	0.965	4.09	4.24	40.2	0.4556	66.08
30.0	0.200	1.038	31.39	30.26	142.5	0.0986	14.29
40.0	0.200	1.030	20.71	20.11	98.3	0.1310	19.00
50.0	0.200	1.021	14.11	13.81	72.9	0.1761	25.54
60.0	0.200	1.013	9.93	9.80	58.3	0.2339	33.93
70.0	0.200	1.005	7.22	7.18	49.6	0.3045	44.16
80.0	0.200	0.997	5.42	5.44	44.0	0.3877	56.23
90.0	0.200	0.988	4.21	4.26	40.3	0.4836	70.14
100.0	0.200	0.980	3.37	3.44	37.6	0.5923	85.90
30.0	0.250	1.056	23.32	22.08	106.6	0.1189	17.25
40.0	0.250	1.048	15.74	15.03	77.5	0.1583	22.96
50.0	0.250	1.039	10.95	10.54	60.8	0.2132	30.93

(continued)

Table 5.11 (continued)

Temp. (°C)	Lubricant (mass frac.)	Density (g/mL)	Viscosity			Pressure	
			(cP)	(cSt)	(SUS)	(MPa)	(psia)
60.0	0.250	1.030	7.85	7.61	50.9	0.2837	41.15
70.0	0.250	1.022	5.79	5.67	44.7	0.3698	53.63
80.0	0.250	1.013	4.41	4.35	40.5	0.4714	68.37
90.0	0.250	1.004	3.45	3.44	37.6	0.5886	85.36
100.0	0.250	0.995	2.79	2.80	35.5	0.7213	104.61
30.0	0.300	1.076	17.36	16.14	81.8	0.1376	19.96
40.0	0.300	1.067	11.99	11.25	63.3	0.1834	26.61
50.0	0.300	1.057	8.52	8.05	52.3	0.2476	35.91
60.0	0.300	1.048	6.21	5.93	45.5	0.3300	47.87
70.0	0.300	1.038	4.66	4.49	40.9	0.4308	62.48
80.0	0.300	1.029	3.59	3.49	37.7	0.5498	79.74
90.0	0.300	1.019	2.84	2.79	35.4	0.6871	99.65
100.0	0.300	1.009	2.31	2.29	33.8	0.8427	122.22
30.0	0.350	1.095	12.94	11.81	65.2	0.1546	22.42
40.0	0.350	1.086	9.15	8.43	53.5	0.2064	29.94
50.0	0.350	1.076	6.64	6.17	46.2	0.2792	40.49
60.0	0.350	1.066	4.93	4.63	41.3	0.3729	54.08
70.0	0.350	1.056	3.75	3.56	37.9	0.4874	70.69
80.0	0.350	1.045	2.93	2.80	35.5	0.6229	90.34
90.0	0.350	1.034	2.34	2.26	33.7	0.7792	113.02
100.0	0.350	1.024	1.92	1.87	32.4	0.9565	138.73
30.0	0.400	1.116	9.66	8.66	54.2	0.1698	24.63
40.0	0.400	1.105	7.00	6.33	46.6	0.2272	32.96
50.0	0.400	1.095	5.18	4.73	41.6	0.3080	44.68
60.0	0.400	1.084	3.92	3.62	38.1	0.4122	59.79
70.0	0.400	1.073	3.03	2.83	35.5	0.5398	78.29
80.0	0.400	1.062	2.40	2.26	33.6	0.6907	100.18
90.0	0.400	1.050	1.94	1.84	32.3	0.8650	125.45
100.0	0.400	1.038	1.60	1.54	31.2	1.0626	154.12
30.0	0.450	1.137	7.23	6.36	46.7	0.1834	26.59
40.0	0.450	1.126	5.36	4.76	41.6	0.2459	35.66
50.0	0.450	1.114	4.05	3.64	38.1	0.3341	48.46
60.0	0.450	1.102	3.12	2.83	35.5	0.4481	64.99
70.0	0.450	1.090	2.45	2.25	33.6	0.5878	85.25
80.0	0.450	1.078	1.97	1.82	32.1	0.7532	109.24
90.0	0.450	1.065	1.60	1.51	31.1	0.9443	136.96
100.0	0.450	1.053	1.33	1.27	30.3	1.1612	168.42
30.0	0.500	1.159	5.41	4.67	41.3	0.1952	28.31
40.0	0.500	1.146	4.11	3.59	37.9	0.2624	38.05
50.0	0.500	1.134	3.18	2.80	35.3	0.3575	51.84
60.0	0.500	1.121	2.49	2.22	33.4	0.4805	69.69
70.0	0.500	1.108	1.99	1.80	32.0	0.6315	91.59
80.0	0.500	1.095	1.62	1.48	30.9	0.8104	117.54
90.0	0.500	1.081	1.33	1.23	30.1	1.0173	147.55
100.0	0.500	1.067	1.12	1.05	29.5	1.2521	181.61

TABLE 5.12: SMOOTHED DATA FOR R-114/ISO68 NAPHTHENIC MINERAL OIL MIXTURES: CONSTANT TEMPERATURE

Temp. (°C)	Lubricant (mass frac.)	Density (g/mL)	Viscosity (cP)	Viscosity (cSt)	Viscosity (SUS)	Pressure (MPa)	Pressure (psia)
20.0	0.000	0.913	171.79	188.09	869.7	0.0000	0.00
20.0	0.050	0.932	108.13	116.02	536.6	0.0436	6.33
20.0	0.100	0.951	69.89	73.47	340.1	0.0828	12.01
20.0	0.150	0.971	46.40	47.76	221.8	0.1174	17.03
20.0	0.200	0.992	31.63	31.88	149.7	0.1475	21.40
20.0	0.250	1.014	22.15	21.85	105.5	0.1731	25.11
20.0	0.300	1.036	15.93	15.37	78.7	0.1942	28.17
20.0	0.350	1.059	11.76	11.10	62.6	0.2108	30.58
20.0	0.400	1.083	8.92	8.24	52.7	0.2229	32.33
20.0	0.450	1.108	6.95	6.27	46.4	0.2305	33.43
20.0	0.500	1.133	5.56	4.91	42.0	0.2336	33.87
30.0	0.000	0.907	89.04	98.13	454.4	0.0000	0.00
30.0	0.050	0.926	59.52	64.28	298.1	0.0559	8.11
30.0	0.100	0.945	40.66	43.01	200.3	0.1057	15.33
30.0	0.150	0.965	28.38	29.40	138.7	0.1493	21.66
30.0	0.200	0.986	20.24	20.53	100.0	0.1869	27.10
30.0	0.250	1.007	14.75	14.64	75.9	0.2183	31.66
30.0	0.300	1.029	10.98	10.67	61.1	0.2435	35.32
30.0	0.350	1.052	8.35	7.94	51.8	0.2627	38.10
30.0	0.400	1.076	6.49	6.04	45.7	0.2757	39.99
30.0	0.450	1.100	5.16	4.69	41.4	0.2826	40.98
30.0	0.500	1.125	4.19	3.72	38.3	0.2833	41.10
40.0	0.000	0.901	49.12	54.50	253.3	0.0000	0.00
40.0	0.050	0.920	34.61	37.62	176.0	0.0704	10.21
40.0	0.100	0.939	24.80	26.41	125.6	0.1330	19.29
40.0	0.150	0.959	18.08	18.86	93.1	0.1879	27.26
40.0	0.200	0.979	13.42	13.70	72.4	0.2351	34.09
40.0	0.250	1.000	10.12	10.12	59.3	0.2745	39.81
40.0	0.300	1.022	7.77	7.60	50.8	0.3061	44.40
40.0	0.350	1.045	6.07	5.81	45.0	0.3301	47.87
40.0	0.400	1.068	4.82	4.52	40.9	0.3462	50.22
40.0	0.450	1.091	3.90	3.57	37.8	0.3547	51.44
40.0	0.500	1.115	3.21	2.87	35.5	0.3554	51.54
50.0	0.000	0.895	28.84	32.22	151.7	0.0000	0.00
50.0	0.050	0.914	21.25	23.25	111.9	0.0871	12.63
50.0	0.100	0.933	15.87	17.01	85.6	0.1648	23.90
50.0	0.150	0.952	12.01	12.61	68.3	0.2332	33.82
50.0	0.200	0.973	9.22	9.48	57.1	0.2922	42.38
50.0	0.250	0.993	7.17	7.22	49.6	0.3418	49.58
50.0	0.300	1.014	5.65	5.57	44.3	0.3821	55.42
50.0	0.350	1.036	4.51	4.36	40.4	0.4130	59.90
50.0	0.400	1.058	3.66	3.46	37.5	0.4346	63.03
50.0	0.450	1.081	3.00	2.78	35.3	0.4468	64.80

(continued)

Table 5.12 (continued)

Temp. (°C)	Lubricant (mass frac.)	Density (g/mL)	Viscosity (cP)	Viscosity (cSt)	Viscosity (SUS)	Pressure (MPa)	Pressure (psia)
50.0	0.500	1.105	2.50	2.26	33.5	0.4496	65.21
60.0	0.000	0.889	18.03	20.27	99.2	0.0000	0.00
60.0	0.050	0.908	13.78	15.18	78.3	0.1060	15.38
60.0	0.100	0.927	10.65	11.49	64.3	0.2010	29.16
60.0	0.150	0.946	8.31	8.79	54.8	0.2851	41.35
60.0	0.200	0.966	6.56	6.80	48.2	0.3582	51.95
60.0	0.250	0.986	5.23	5.31	43.5	0.4203	60.95
60.0	0.300	1.006	4.22	4.19	39.9	0.4714	68.37
60.0	0.350	1.027	3.44	3.35	37.2	0.5115	74.19
60.0	0.400	1.048	2.83	2.70	35.0	0.5407	78.42
60.0	0.450	1.070	2.35	2.20	33.4	0.5589	81.06
60.0	0.500	1.092	1.98	1.81	32.0	0.5661	82.10
70.0	0.000	0.883	11.99	13.58	72.1	0.0000	0.00
70.0	0.050	0.902	9.44	10.47	60.7	0.1272	18.44
70.0	0.100	0.920	7.49	8.14	52.7	0.2417	35.06
70.0	0.150	0.939	6.00	6.39	47.0	0.3437	49.85
70.0	0.200	0.958	4.84	5.05	42.7	0.4331	62.81
70.0	0.250	0.978	3.94	4.03	39.4	0.5098	73.94
70.0	0.300	0.997	3.23	3.24	36.9	0.5740	83.25
70.0	0.350	1.017	2.68	2.63	34.9	0.6256	90.73
70.0	0.400	1.038	2.23	2.15	33.2	0.6646	96.39
70.0	0.450	1.058	1.88	1.78	31.9	0.6909	100.21
70.0	0.500	1.079	1.60	1.48	30.9	0.7047	102.21
80.0	0.000	0.877	8.49	9.68	58.0	0.0000	0.00
80.0	0.050	0.895	6.83	7.62	51.1	0.1505	21.83
80.0	0.100	0.914	5.53	6.05	45.9	0.2868	41.60
80.0	0.150	0.932	4.51	4.84	42.1	0.4089	59.31
80.0	0.200	0.951	3.70	3.89	39.0	0.5168	74.96
80.0	0.250	0.969	3.06	3.16	36.6	0.6105	88.55
80.0	0.300	0.988	2.55	2.58	34.7	0.6900	100.07
80.0	0.350	1.007	2.13	2.12	33.2	0.7552	109.53
80.0	0.400	1.026	1.80	1.75	31.9	0.8062	116.93
80.0	0.450	1.045	1.53	1.46	30.9	0.8430	122.27
80.0	0.500	1.064	1.31	1.23	30.1	0.8656	125.55
90.0	0.000	0.871	6.40	7.34	50.2	0.0000	0.00
90.0	0.050	0.889	5.22	5.87	45.4	0.1761	25.54
90.0	0.100	0.907	4.28	4.72	41.7	0.3364	48.79
90.0	0.150	0.925	3.53	3.82	38.8	0.4809	69.74
90.0	0.200	0.943	2.93	3.11	36.5	0.6095	88.40
90.0	0.250	0.961	2.45	2.55	34.7	0.7223	104.76
90.0	0.300	0.978	2.06	2.10	33.1	0.8192	118.82
90.0	0.350	0.996	1.74	1.75	31.9	0.9004	130.59
90.0	0.400	1.013	1.48	1.46	30.9	0.9657	140.06
90.0	0.450	1.030	1.27	1.23	30.1	1.0151	147.23

(continued)

Table 5.12 (continued)

Temp. (°C)	Lubricant (mass frac.)	Density (g/mL)	Viscosity (cP)	Viscosity (cSt)	Viscosity (SUS)	Pressure (MPa)	Pressure (psia)
90.0	0.500	1.048	1.09	1.04	29.4	1.0488	152.11
100.0	0.000	0.865	5.13	5.93	45.7	0.0000	0.00
100.0	0.050	0.883	4.21	4.77	41.9	0.2039	29.58
100.0	0.100	0.901	3.47	3.86	39.0	0.3904	56.63
100.0	0.150	0.918	2.88	3.14	36.7	0.5594	81.14
100.0	0.200	0.935	2.41	2.57	34.8	0.7110	103.13
100.0	0.250	0.952	2.02	2.12	33.3	0.8452	122.58
100.0	0.300	0.968	1.71	1.76	32.0	0.9619	139.50
100.0	0.350	0.984	1.45	1.48	31.0	1.0611	153.90
100.0	0.400	1.000	1.24	1.24	30.2	1.1429	165.76
100.0	0.450	1.015	1.07	1.05	29.5	1.2072	175.09
100.0	0.500	1.030	0.92	0.90	28.9	1.2541	181.89

TABLE 5.13: SMOOTHED DATA FOR R-114/ISO68 NAPHTHENIC MINERAL OIL MIXTURES: CONSTANT CONCENTRATION

Temp. (°C)	Lubricant (mass frac.)	Density (g/mL)	Viscosity (cP)	Viscosity (cSt)	Viscosity (SUS)	Pressure (MPa)	Pressure (psia)
20.0	0.000	0.913	171.79	188.09	869.7	0.0000	0.00
30.0	0.000	0.907	89.04	98.13	454.4	0.0000	0.00
40.0	0.000	0.901	49.12	54.50	253.3	0.0000	0.00
50.0	0.000	0.895	28.84	32.22	151.7	0.0000	0.00
60.0	0.000	0.889	18.03	20.27	99.2	0.0000	0.00
70.0	0.000	0.883	11.99	13.58	72.1	0.0000	0.00
80.0	0.000	0.877	8.49	9.68	58.0	0.0000	0.00
90.0	0.000	0.871	6.40	7.34	50.2	0.0000	0.00
100.0	0.000	0.865	5.13	5.93	45.7	0.0000	0.00
20.0	0.050	0.932	108.13	116.02	536.6	0.0436	6.33
30.0	0.050	0.926	59.52	64.28	298.1	0.0559	8.11
40.0	0.050	0.920	34.61	37.62	176.0	0.0704	10.21
50.0	0.050	0.914	21.25	23.25	111.9	0.0871	12.63
60.0	0.050	0.908	13.78	15.18	78.3	0.1060	15.38
70.0	0.050	0.902	9.44	10.47	60.7	0.1272	18.44
80.0	0.050	0.895	6.83	7.62	51.1	0.1505	21.83
90.0	0.050	0.889	5.22	5.87	45.4	0.1761	25.54
100.0	0.050	0.883	4.21	4.77	41.9	0.2039	29.58
20.0	0.100	0.951	69.89	73.47	340.1	0.0828	12.01
30.0	0.100	0.945	40.66	43.01	200.3	0.1057	15.33
40.0	0.100	0.939	24.80	26.41	125.6	0.1330	19.29
50.0	0.100	0.933	15.87	17.01	85.6	0.1648	23.90
60.0	0.100	0.927	10.65	11.49	64.3	0.2010	29.16
70.0	0.100	0.920	7.49	8.14	52.7	0.2417	35.06

(continued)

Table 5.13 (continued)

Temp. (°C)	Lubricant (mass frac.)	Density (g/mL)	Viscosity (cP)	Viscosity (cSt)	Viscosity (SUS)	Pressure (MPa)	Pressure (psia)
80.0	0.100	0.914	5.53	6.05	45.9	0.2868	41.60
90.0	0.100	0.907	4.28	4.72	41.7	0.3364	48.79
100.0	0.100	0.901	3.47	3.86	39.0	0.3904	56.63
20.0	0.150	0.971	46.40	47.76	221.8	0.1174	17.03
30.0	0.150	0.965	28.38	29.40	138.7	0.1493	21.66
40.0	0.150	0.959	18.08	18.86	93.1	0.1879	27.26
50.0	0.150	0.952	12.01	12.61	68.3	0.2332	33.82
60.0	0.150	0.946	8.31	8.79	54.8	0.2851	41.35
70.0	0.150	0.939	6.00	6.39	47.0	0.3437	49.85
80.0	0.150	0.932	4.51	4.84	42.1	0.4089	59.31
90.0	0.150	0.925	3.53	3.82	38.8	0.4809	69.74
100.0	0.150	0.918	2.88	3.14	36.7	0.5594	81.14
20.0	0.200	0.992	31.63	31.88	149.7	0.1475	21.40
30.0	0.200	0.986	20.24	20.53	100.0	0.1869	27.10
40.0	0.200	0.979	13.42	13.70	72.4	0.2351	34.09
50.0	0.200	0.973	9.22	9.48	57.1	0.2922	42.38
60.0	0.200	0.966	6.56	6.80	48.2	0.3582	51.95
70.0	0.200	0.958	4.84	5.05	42.7	0.4331	62.81
80.0	0.200	0.951	3.70	3.89	39.0	0.5168	74.96
90.0	0.200	0.943	2.93	3.11	36.5	0.6095	88.40
100.0	0.200	0.935	2.41	2.57	34.8	0.7110	103.13
20.0	0.250	1.014	22.15	21.85	105.5	0.1731	25.11
30.0	0.250	1.007	14.75	14.64	75.9	0.2183	31.66
40.0	0.250	1.000	10.12	10.12	59.3	0.2745	39.81
50.0	0.250	0.993	7.17	7.22	49.6	0.3418	49.58
60.0	0.250	0.986	5.23	5.31	43.5	0.4203	60.95
70.0	0.250	0.978	3.94	4.03	39.4	0.5098	73.94
80.0	0.250	0.969	3.06	3.16	36.6	0.6105	88.55
90.0	0.250	0.961	2.45	2.55	34.7	0.7223	104.76
100.0	0.250	0.952	2.02	2.12	33.3	0.8452	122.58
20.0	0.300	1.036	15.93	15.37	78.7	0.1942	28.17
30.0	0.300	1.029	10.98	10.67	61.1	0.2435	35.32
40.0	0.300	1.022	7.77	7.60	50.8	0.3061	44.40
50.0	0.300	1.014	5.65	5.57	44.3	0.3821	55.42
60.0	0.300	1.006	4.22	4.19	39.9	0.4714	68.37
70.0	0.300	0.997	3.23	3.24	36.9	0.5740	83.25
80.0	0.300	0.988	2.55	2.58	34.7	0.6900	100.07
90.0	0.300	0.978	2.06	2.10	33.1	0.8192	118.82
100.0	0.300	0.968	1.71	1.76	32.0	0.9619	139.50
20.0	0.350	1.059	11.76	11.10	62.6	0.2108	30.58
30.0	0.350	1.052	8.35	7.94	51.8	0.2627	38.10
40.0	0.350	1.045	6.07	5.81	45.0	0.3301	47.87
50.0	0.350	1.036	4.51	4.36	40.4	0.4130	59.90
60.0	0.350	1.027	3.44	3.35	37.2	0.5115	74.19

(continued)

Table 5.13 (continued)

Temp. (°C)	Lubricant (mass frac.)	Density (g/mL)	Viscosity (cP)	(cSt)	(SUS)	Pressure (MPa)	(psia)
70.0	0.350	1.017	2.68	2.63	34.9	0.6256	90.73
80.0	0.350	1.007	2.13	2.12	33.2	0.7552	109.53
90.0	0.350	0.996	1.74	1.75	31.9	0.9004	130.59
100.0	0.350	0.984	1.45	1.48	31.0	1.0611	153.90
20.0	0.400	1.083	8.92	8.24	52.7	0.2229	32.33
30.0	0.400	1.076	6.49	6.04	45.7	0.2757	39.99
40.0	0.400	1.068	4.82	4.52	40.9	0.3462	50.22
50.0	0.400	1.058	3.66	3.46	37.5	0.4346	63.03
60.0	0.400	1.048	2.83	2.70	35.0	0.5407	78.42
70.0	0.400	1.038	2.23	2.15	33.2	0.6646	96.39
80.0	0.400	1.026	1.80	1.75	31.9	0.8062	116.93
90.0	0.400	1.013	1.48	1.46	30.9	0.9657	140.06
100.0	0.400	1.000	1.24	1.24	30.2	1.1429	165.76
20.0	0.450	1.108	6.95	6.27	46.4	0.2305	33.43
30.0	0.450	1.100	5.16	4.69	41.4	0.2826	40.98
40.0	0.450	1.091	3.90	3.57	37.8	0.3547	51.44
50.0	0.450	1.081	3.00	2.78	35.3	0.4468	64.80
60.0	0.450	1.070	2.35	2.20	33.4	0.5589	81.06
70.0	0.450	1.058	1.88	1.78	31.9	0.6909	100.21
80.0	0.450	1.045	1.53	1.46	30.9	0.8430	122.27
90.0	0.450	1.030	1.27	1.23	30.1	1.0151	147.23
100.0	0.450	1.015	1.07	1.05	29.5	1.2072	175.09
20.0	0.500	1.133	5.56	4.91	42.0	0.2336	33.87
30.0	0.500	1.125	4.19	3.72	38.3	0.2833	41.10
40.0	0.500	1.115	3.21	2.87	35.5	0.3554	51.54
50.0	0.500	1.105	2.50	2.26	33.5	0.4496	65.21
60.0	0.500	1.092	1.98	1.81	32.0	0.5661	82.10
70.0	0.500	1.079	1.60	1.48	30.9	0.7047	102.21
80.0	0.500	1.064	1.31	1.23	30.1	0.8656	125.55
90.0	0.500	1.048	1.09	1.04	29.4	1.0488	152.11
100.0	0.500	1.030	0.92	0.90	28.9	1.2541	181.89

Graphical Results

With the use of the above correlating equations, plots of solubility, viscosity, and density can be produced. Graphical results for the solubility of R-236ea/ISO68 pentaerythritol ester mixed-acid and R-114/ISO68 naphthenic mineral oil mixtures are given in Figures 5.4 and 5.5. Figures 5.4 and 5.5, which are plots of pressure vs. refrigerant concentration for a range of temperatures, show that the pressure increases with increasing refrigerant concentration and temperature.

Figures 5.6 and 5.7 provide the results of the correlation equations for absolute viscosity as a function of temperature and refrigerant mass fraction. Figures 5.8 and 5.9 provide kinematic viscosity as a function of temperature and refrigerant mass fraction. It should be noted that these semilogarithmic graphs are different from an ASTM chart where kinematic viscosity is plotted vs. temperature on non-linear axes. The temperature range is from 40°C (104°F) to 100°C (212°F). Similarly, the results for the mixture density are given in Figures 5.10 and 5.11. The results show that density decreases with increasing temperature for any refrigerant composition.

Summary

Data have been collected for R-236ea/ISO68 pentaerythritol ester mixed-acid and R-114/ISO68 naphthenic mineral oil mixtures. These tests provide solubility, density, and viscosity information for temperatures as high as 100°C (212°F) and for pressures up to 1.4 MPa (200 psia). The results are presented as solubility, viscosity, and density charts, as well as in graphical form. The solubility graphs show pressure as a function of temperature, while the viscosity and density graphs show liquid viscosity and liquid density as functions of refrigerant concentration. Also provided are empirical correlating equations (applicable only over the range of data collected) that allow convenient interpolation of the data.

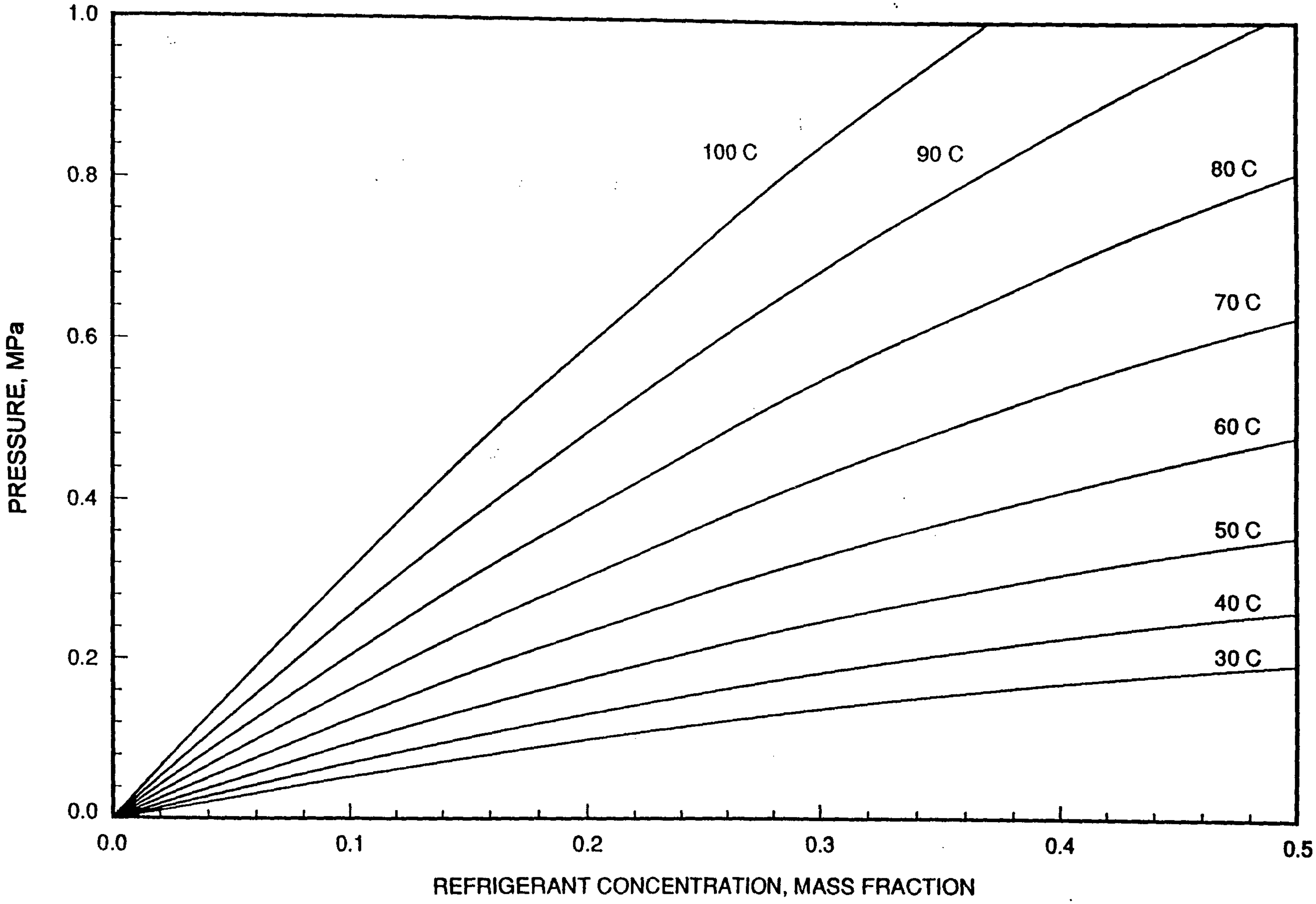

Figure 5.4 Solubility of R-236ea in Castrol SW68.

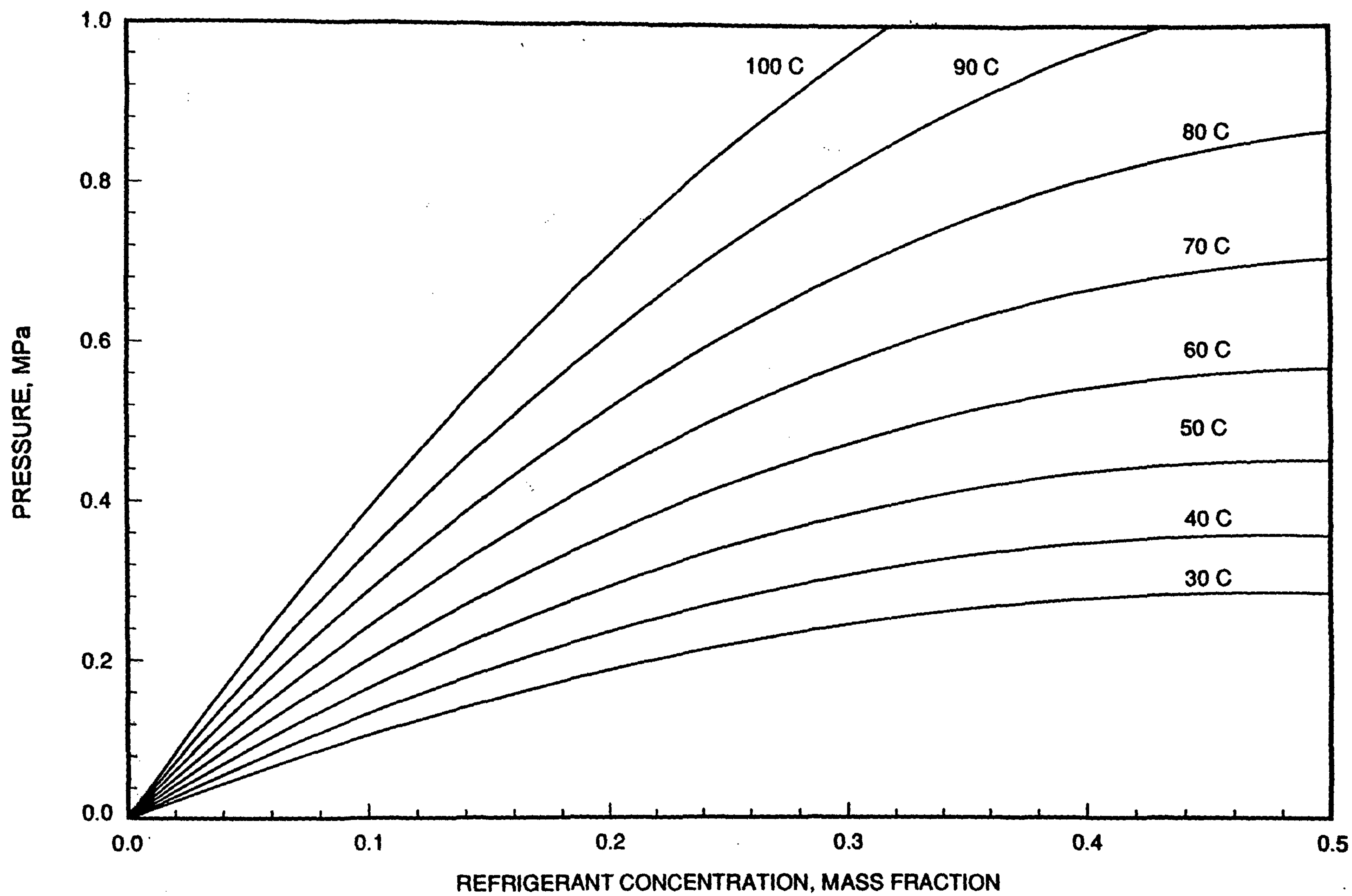

Figure 5.5 Solubility of R-114 in York C.

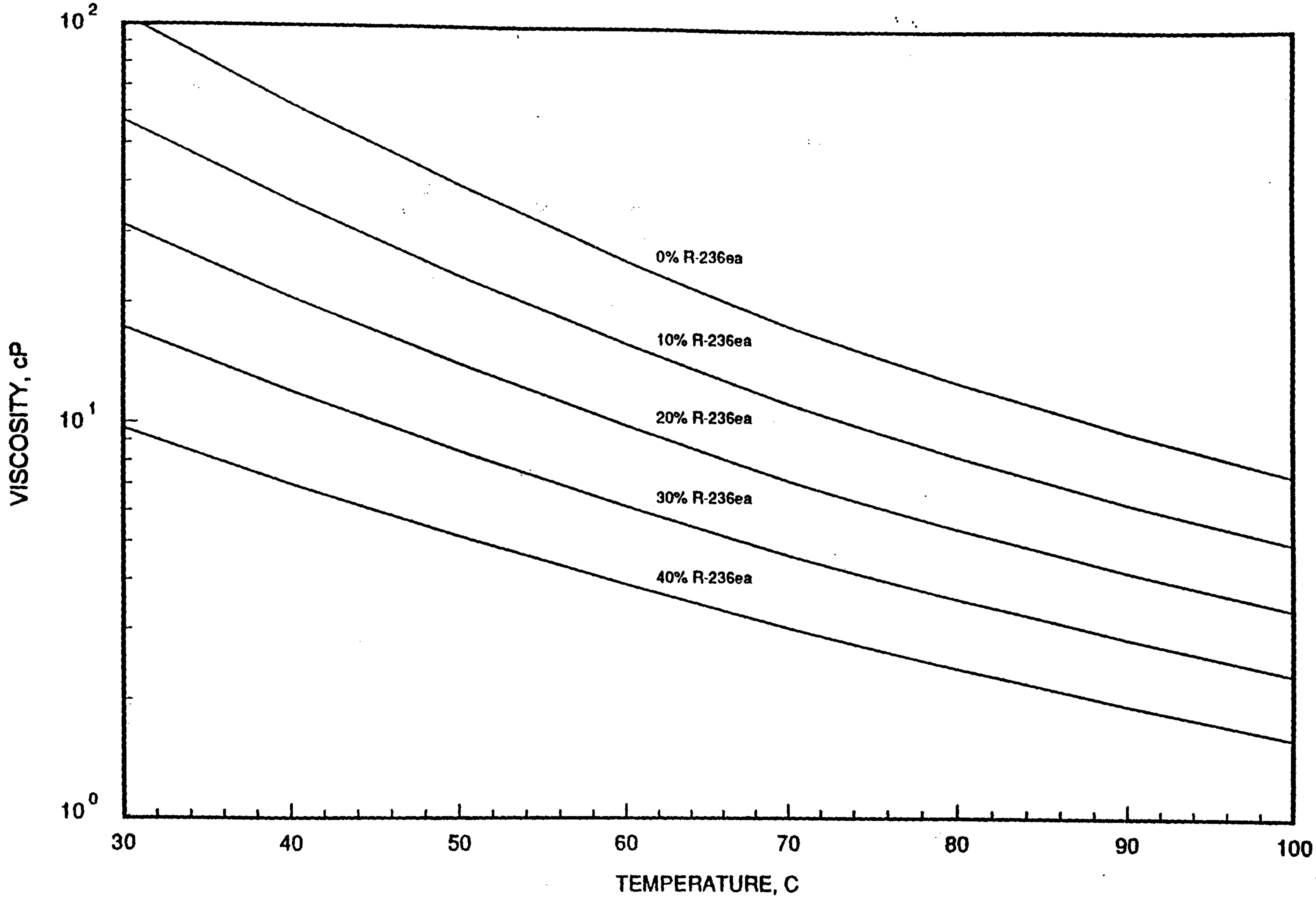

Figure 5.6 Absolute viscosity of mixtures of R-236ea and Castrol SW68.

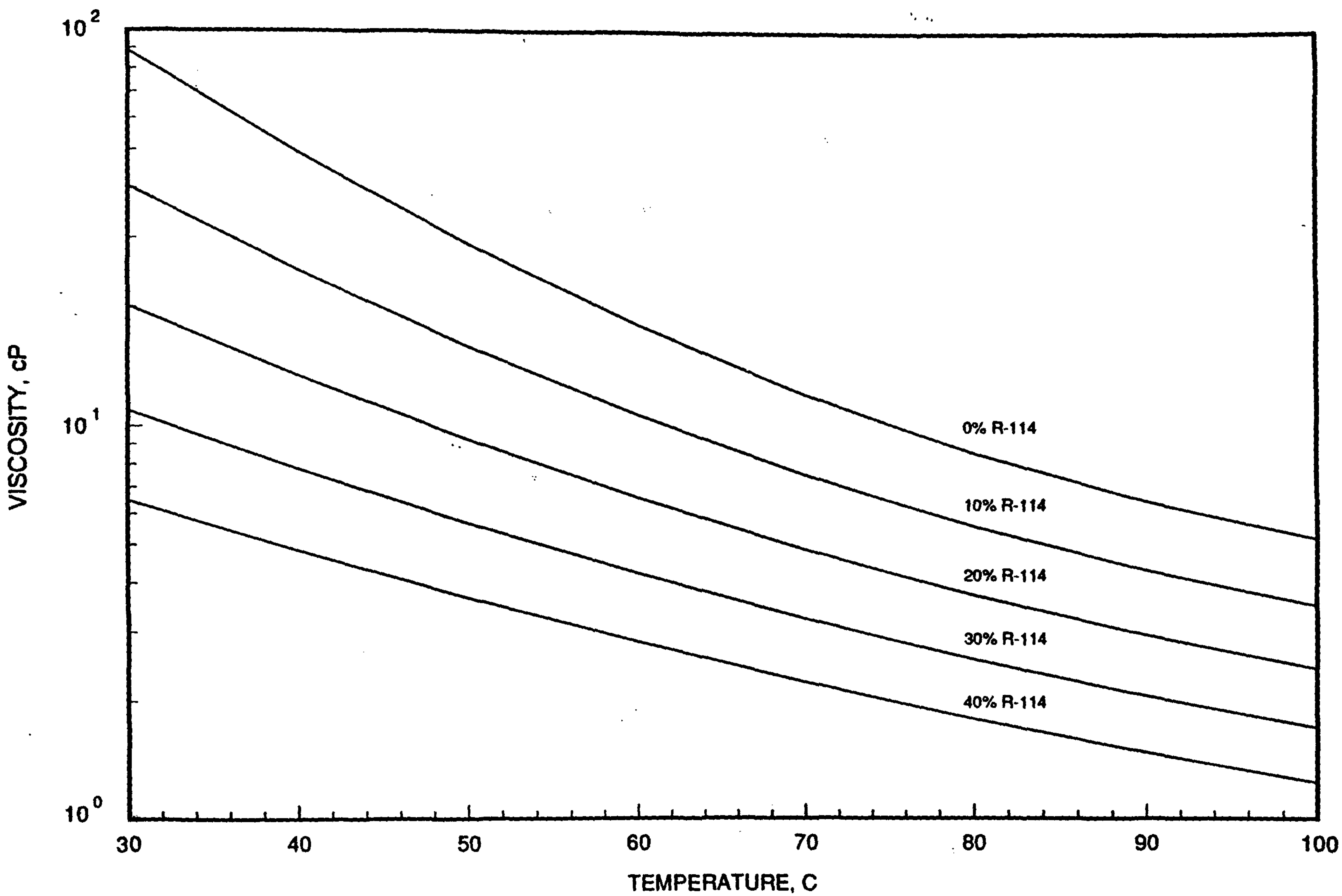

Figure 5.7 Absolute viscosity of mixtures of R-114 and York C.

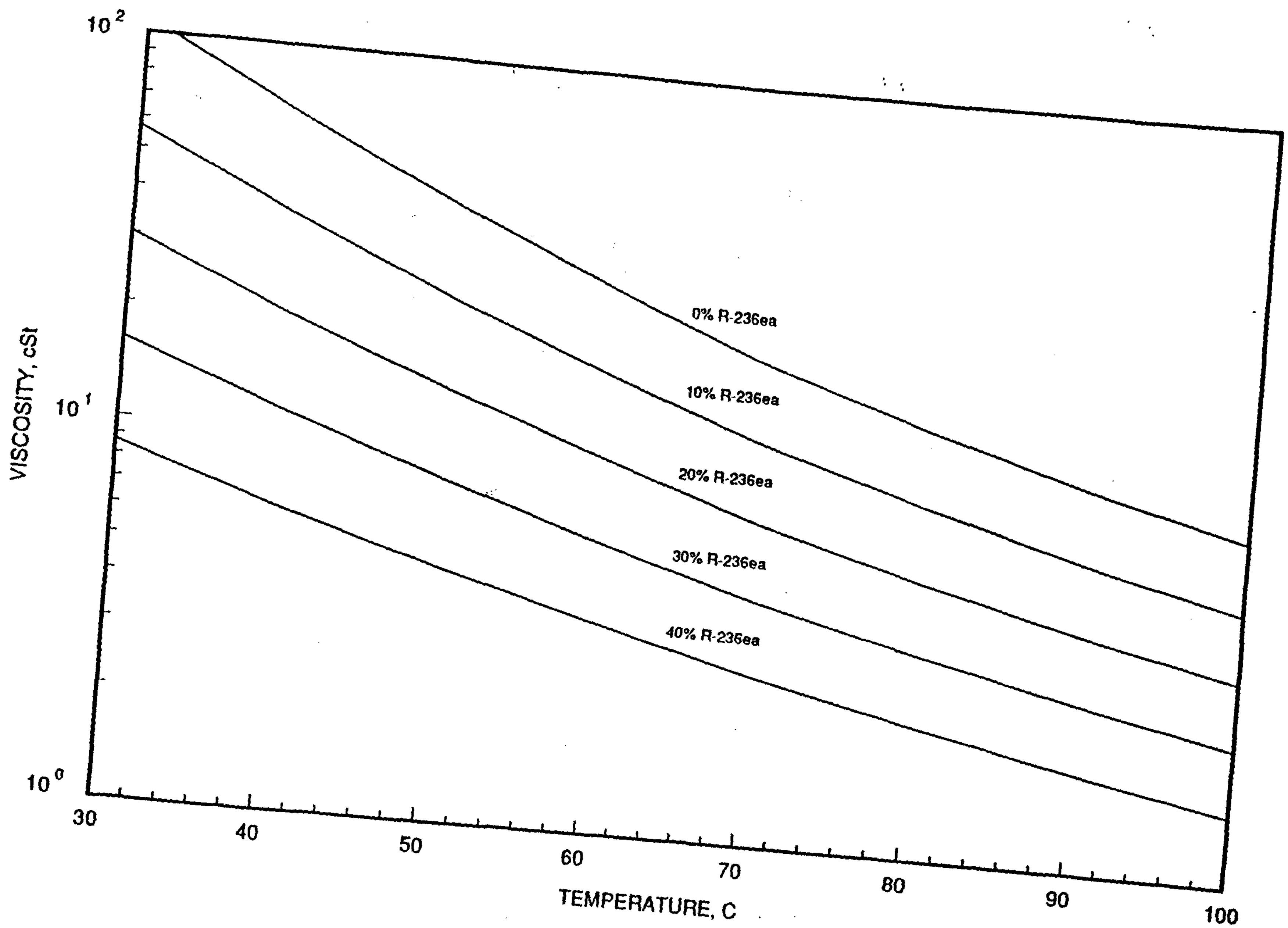

Figure 5.8 Kinematic viscosity of mixtures of R-236ea and Castrol SW68.

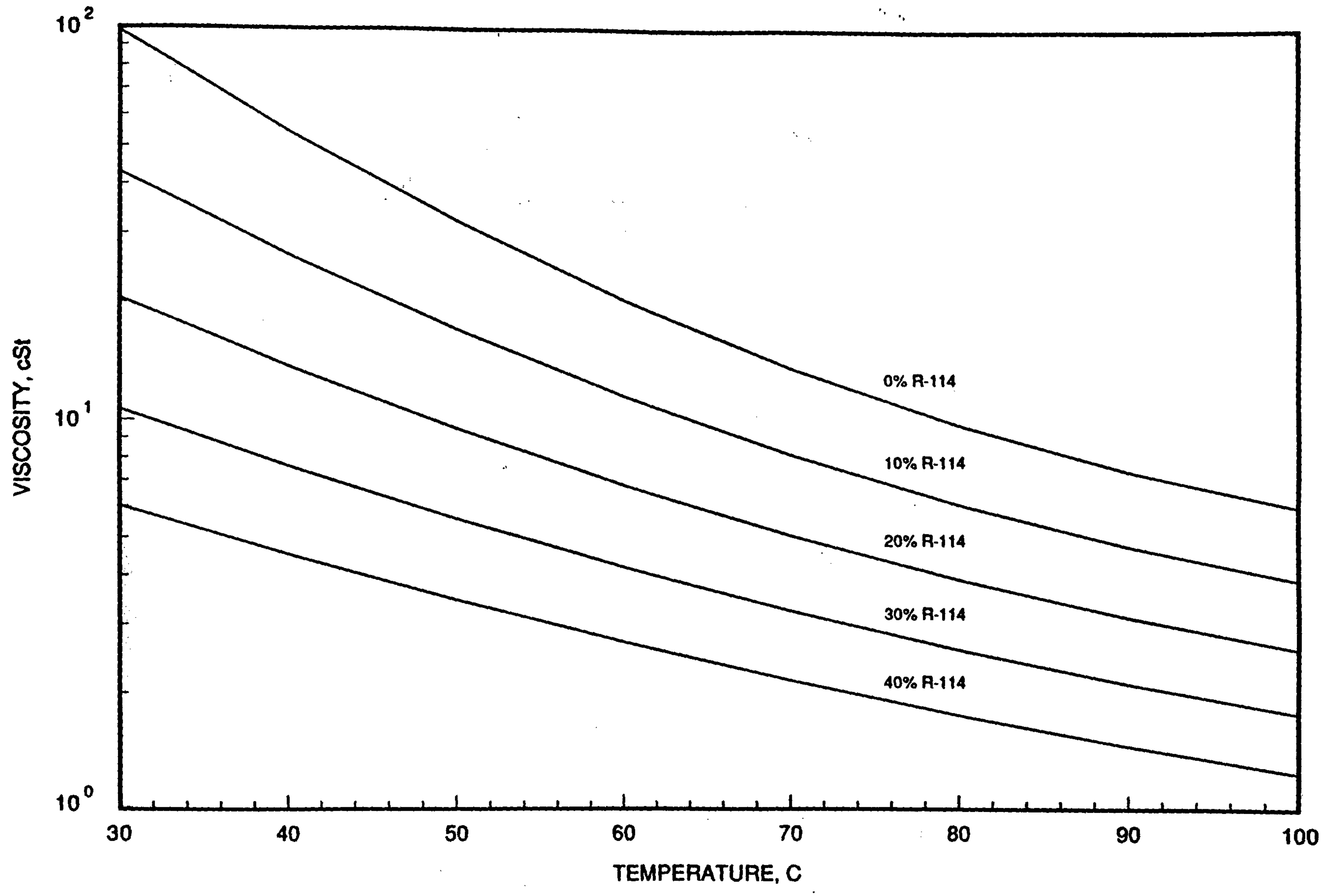

Figure 5.9 Kinematic viscosity of mixtures of R-114 and York C.

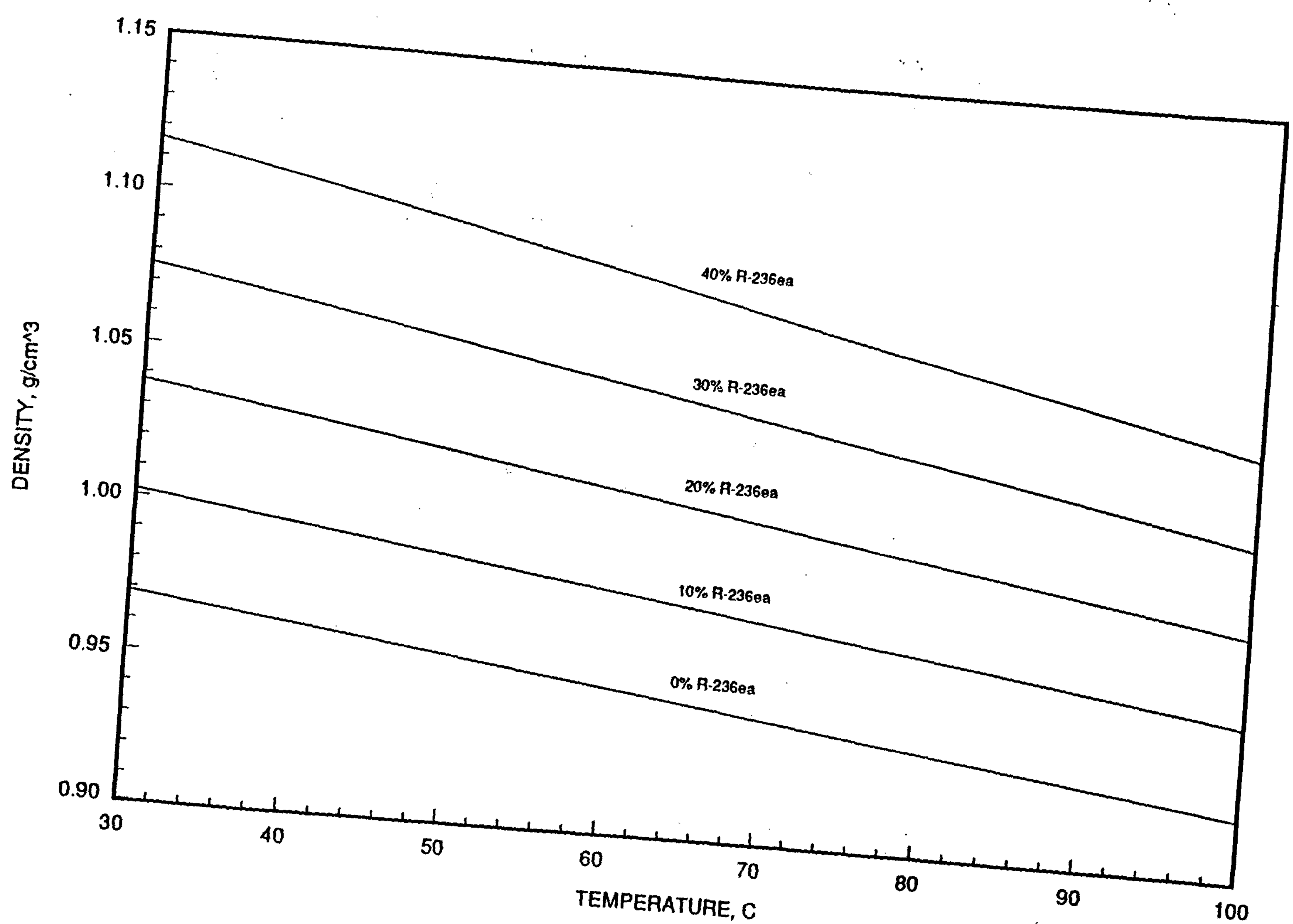

Figure 5.10 Density of mixtures of R-236ea and Castrol SW68.

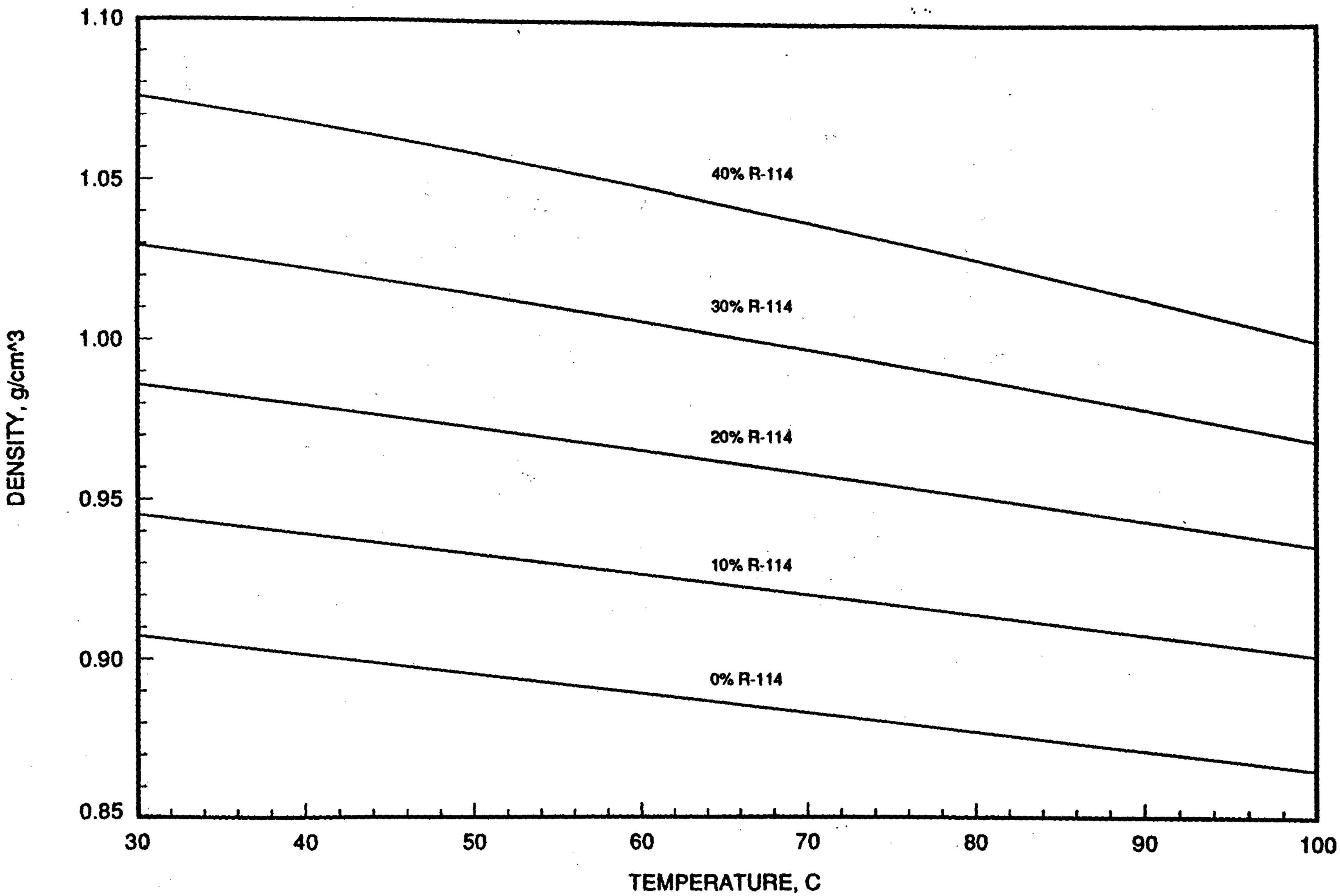

Figure 5.11 Density of mixtures of R-114 and York C.

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16. ABSTRACT The report gives results of miscibility, solubility, and viscosity measurements of refrigerant R-236ea with three potential lubricants. (NOTE: The data were needed to determine the suitability of refrigerant/lubricant combinations for use in refrigeration systems.) The lubricants were a mineral oil, alkylbenzene, and polyol ester, each with a nominal viscosity of 68 cSt. The miscibility tests were performed in a test facility consisting of a series of miniature test cells in a constant-temperature bath. The bath temperature was precisely controlled over a range of -50 to 90°C (-58 to 194°F). The test cells are constructed to allow for complete visibility of the refrigerant/lubricant mixtures under all test conditions. Critical solution temperatures obtained from the miscibility data are presented for each refrigerant/lubricant combination. In addition to miscibility data, both solubility and viscosity data were obtained for R-236ea and the most promising lubricant. These data were obtained for a refrigerant concentration range of 0 to 40 wt % refrigerant over a temperature range of 40 to 120°C. This range of conditions represents the area of interest necessary for the proper design of compressors. For comparison purposes, data were also taken for the existing U. S. Navy shipboard chiller refrigerant and lubricant concentration, namely R-114 and a naphthenic oil.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Aromatic Monocyclic Hydrocarbons	Pollution Control	13B	
Refrigerants		Stationary Sources	13A	07C
Lubricants	Esters	Refrigeration Systems	11H	
Solubility		Alkylbenzene	07D	
Viscosity		Polyol Ester	20D	
Mineral Oils				

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